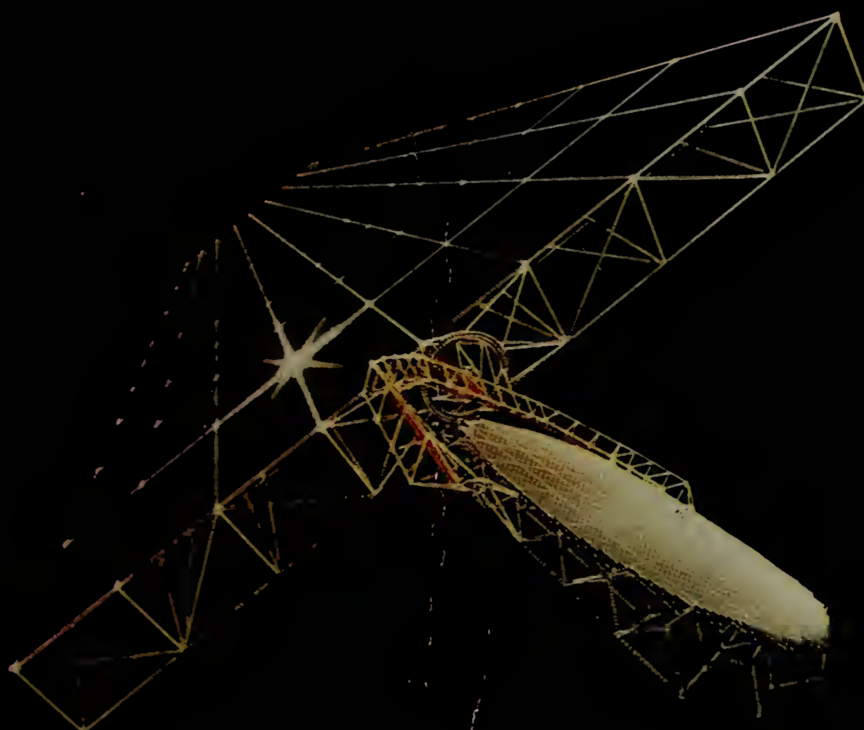
SECOND INTERNATIONAL SYMPOSIUM

SPS 91

POWER FROM SPACE

PARIS/GIF-SUR-YVETTE
27 to 30 AUGUST 1991



see

SOCIÉTÉ
DES INGÉNIEURS
ET SCIENTIFIQUES
DE FRANCE

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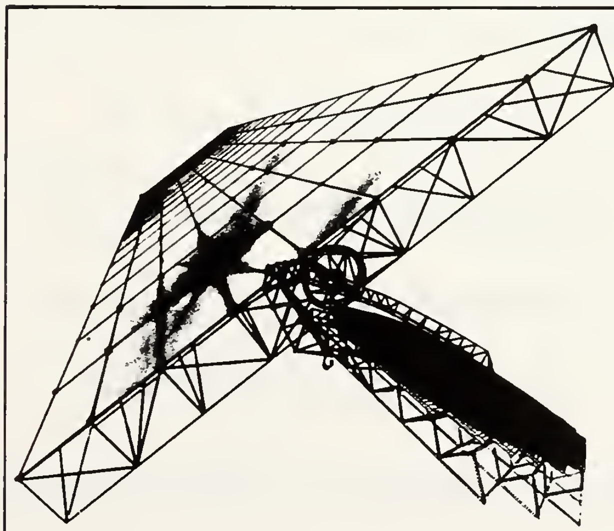

SPS 91

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Alenia Spazio S.p.A. (I).

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Furukawa Electric Co Ltd (J).

Ministère de la Défense (F).

Ministère de la Recherche et de la Technologie (F).

Space Studies Institute (USA).

We would like to thank the above organizations for their generous support without which this symposium would not have been possible.

CONTENTS

ORGANIZED BY :

- **Société des Electriciens et des Electroniciens (SEE)**

- **Société des Ingénieurs et Scientifiques de France (ISF)**

With the support of Professor ***Hubert CURIEN,***
French Minister of Research and Technology,
and the honorary sponsorship
of the ***United Nations*** *Centre for Science*
and Technology for Development.

SPONSORED BY :

- IAF - International Astronautical Federation
- AIAA - American Institute of Aeronautics and Astronautics
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- National Space Society
- The planetary Society
- Sunsat Energy Council
- Space Studies Institute
- International Solar Energy Society
- Intercosmos Council - USSR Academy of Sciences
- The British Interplanetary Society
- Deutsche Gesellschaft für Luft und Raumfahrt E.V.
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- Association Aéronautique et Astronautique de France
- Israel Society of Aeronautics and Astronautics
- Japanese Rocket Society
- IEEE - French Section and PES Chapter
- UNIPEDE - International Union of Producers and Distributors of Electric Energy
- Association Internationale FUTURIBLES
- COFEDES - Cooperation Française pour l'Etude et le Développement de l'Energie Solaire
- Medispace - Société Française d'Etude et de Recherche en Médecine Spatiale.

OBJECTIVES AND GENERAL TOPICS

The utilization of solar energy for large scale power generation is hampered on Earth by the fluctuations in the energy received. A large capacity power plant placed in geostationary orbit would be illuminated nearly continuously and would thus supply baseload electricity.

Since the proposal for this Solar Power Satellite concept made by Peter Glaser in 1968, numerous studies have been carried out especially between 1978 and 1981 in the framework of a program undertaken by the Department of Energy and NASA in the United States.

Today, a decade after this program, several individuals and small research groups are still working toward developing a future for this promising concept. Also, recent technology advancements associated with the international space station Freedom, the U.S. Strategic Defense Initiative, and other current space programs have improved the feasibility prospects for SPS concepts that in the past were often speculative.

The SPS 91 "Power from space" symposium will assess the state-of-the-art of technologies needed to build and operate an SPS, to promote research on new SPS concepts, to evaluate the associated environmental and societal issues, and, in general, to promote interest in the SPS concept.

This Symposium will build on and extend the information base established by the "Solar Power Satellites" Symposium organized by the SEE in PARIS 5-6 June, 1986.

The following topics will be covered :

1 - Global energy issue and societal challenge (2 sessions)

2 - Technology status - Transportation (1 session)

3 - Technology status - Power generation, conversion and storage (3 sessions)

4 - Technology status - Transmission (2 sessions)

5 - Technology status - Systems (3 sessions)

6 - Extraterrestrial materials (1 session)

7 - Environmental issues (1 session)

8 - SPS development strategies (1 session)

9 - Demonstration projects (2 sessions).

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Dr. KOTELNIKOV X. *(Intercosmos Council)* - USSR
Dr. MARCHAL Ch. *(ONERA)* - France
Dr. MARTIN A.R. *(Culham Laboratory)* - UK
Dr. MARYNIAK G. *(Space Studies Institute)* - USA
Dr. MAYUR R. *(Urban Development Institute)* - India
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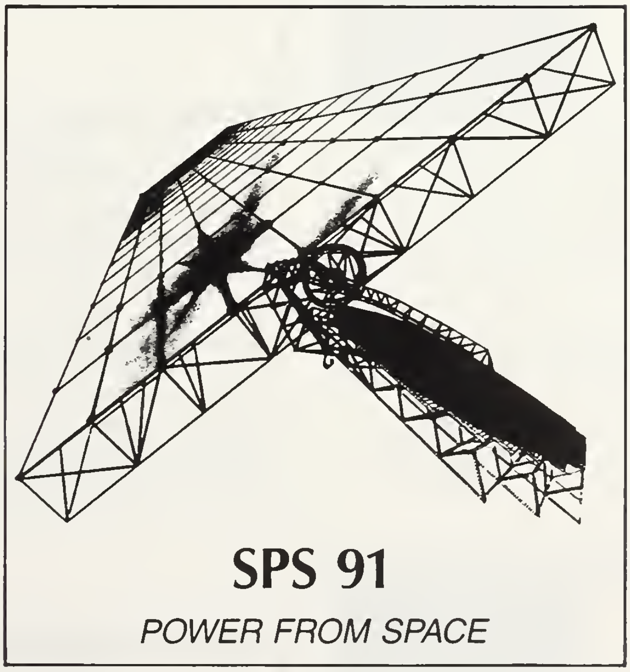

Room A = Sessions A_1 to A_8 and plenary sessions Room B = Sessions B_1 to B_8. Room C = Poster Session C	**SPS 91 - POWER FROM SPACE** **27 to 30 AUGUST 1991** **ÉCOLE SUPÉRIEURE D'ÉLECTRICITÉ (SUPELEC)** **Plateau de Moulon - 91190 GIF-SUR-YVETTE**		
Tuesday August 27th	9.00 - 17.00 Technical visits V_1 to V_4 (except visit V_1 : 9.00 - 19.30) 17.30 Room A - ISF Lecture - Frank DAVIDSON - MIT - **Toward Planet-wide coalitions for large-scale projects**		
Wednesday August 28 th	8.45 - 12.45 **Opening ceremony - Plenary lectures** I_0 to I_5		C: **Space Power** Poster Session from Wednesday morning to Friday evening
	14.15 - 16.00 A_1: **Global energy issue** (1)	14.15 - 16.00 B_1: **SPS Demonstration Projects** (1)	
	16.30 - 18.30 A_2: **Global energy issue and Societal challenge** (2)	16.30 - 18.30 B_2: **SPS Demonstration Projects** (2)	
	18.45 - 19.45 **Free opinion forum**		
Thursday August 29th	8.30 - 9.15 **Plenary lecture** I_6		
	9.15 - 11.15 A_3: **Extraterrestrial materials**	9.20 - 10.55 B_3: **Technology status: Power generation, conversion and storage** (1)	
	11.35 - 12.30 A_4: **Environmental issues**	11.15 - 12.30 B_4: **Technology status: Power generation, conversion and storage** (2)	
	14.00 - 15.45 A_5: **Technology status: systems** (1)	14.00 - 15.45 B_5: **Technology status: Power generation, conversion and storage** (3)	
	16.15 - 18.20 A_6: **Technology status: systems** (2)	16.15 - 18.20 B_6: **Technology status: Transportation**	
	20.00 **Cocktail Party** - Eiffel Tower		
Friday August 30th	8.30 - 10.15 A_7: **Development strategy**	8.30 - 10.15 B_7: **Technology status: Transmission** (1)	
	10.45 - 12.30 A_8: **Technology status: systems** (3)	10.45 - 12.30 B_8: **Technology status: Transmission** (2)	
	14.00 - 14.45 **Plenary lecture** I_7		
	14.45 - 16.00 Round table: **Towards an international cooperation for SPS evaluation and development: objectives? how?**		
	16.00 - 16.30 **Synthesis of the SPS 91 Symposium** 16.30 **End of SPS 91 Symposium**		

PLENARY LECTURES

I_0 : **SPS and the next century**
Thierry GAUDIN - French Ministery of Research and Technology, Paris - France

I_1 : **Human Exploration of Space and Power Development**
Aaron COHEN - NASA, Houston - USA

I_2 : **SPS interest and studies in USSR**
Vladimir PRISNJAKOV - Dniepropetrovsk State University - USSR

I_3 : **New Earth 21, Action Program**
Jun OKUMURA - MITI, Tokyo - Japan

I_4 : **GSEK - Global Solar Energy Concept**
Johann SPIES - MBB/ERNO, Bremen - FRG

I_5 : **Energy Crisis: SPS for Third World Future**
Rashmi MAYUR - Global Futures Network, Bombay - India

I_6 : **Economic Viability of using the Moon to supply energy to Earth**
Ivan BEKEY - National Space Council - USA

I_7 : **The Solar Power Satellites option re-examined**
Peter GLASER - AD Little, Cambridge - USA

TECHNICAL VISITS

V_1 — PALUEL NUCLEAR POWER PLANT

The Paluel nuclear power plant, situated on the Channel Coast, near Saint-Valéry-en-Caux (Normandy), comprises 4 identical pressurised water reactor units, with rated power of 1300 MW. This power level is still unique in the world for this type of plant.

The first unit was commissioned in 1984, the last one in 1986.

Visitors will see the very peculiar plant site, and the industrial design of the buildings. The visit will show the engine room, the computer control system and the distilled water production plant.

V_2 — AEROSPATIALE

After a presentation of the Aérospatiale Group, attendees will visit the launch integration assembly, the welding workshop of the Ariane 4 first stage,...

V_3 — SEP

After a presentation of the Société Européenne de Propulsion (SEP) activities, attendees will visit the exhibition hall devoted to the propulsion of the present and of the future Ariane launcher. They will also see satellite equipment and some highly significant places :

- Integration shops of the Ariane 4 propulsion systems and of the Ariane 5 rocket engine.

- The facilities area.

V_4 — FREE ELECTRON LASERS

Attendees will visit at the Commissariat à l'Energie Atomique (Atomic Energy Commission) a very powerful free electron laser in the infrared wavelength range.
They will also be given a presentation of the company LASERDOT.
Finally, they will see some of the new laser applications :
- for defense : the LATEX project (high power laser with an experimental turret)
- Adaptive optics for correction of atmospheric turbulences.

SESSION CHAIRMEN AND RAPPORTEURS

Opening Session
Co-Chairmen : Maurice CLAVERIE (CNRS, France)
Peter GLASER (AD Little, USA)

Session A_1
Chairman : Arnaldo ANGELINI (ENEL, Academia dei Lincei, University of Rome, Italy)
Rapporteur : Christian VERIÉ (CNRS, France)

Session A_2
Chairman : Pr. ARISMUNANDAR (Ministry of Mines and Energy, Indonesia)
Rapporteur : François MOISAN (AFME, France)

Session A_3
Chairman : Ivan BEKEY (National Space Council, USA)
Rapporteur : Gilbert PAYAN (Ministère de la Recherche et de la Technologie, France)

Session A_4
Chairman : Anthony R. MARTIN (AEA Technology, UK)
Rapporteur : Michel HORS (Commissariat Général au Plan, France)

Session A_5
Chairman : Frederick KOOMANOFF (DOE, USA)
Rapporteur : Michel DUCHET (LASERDOT, France)

Session A_6
Chairman : Marco BERNASCONI (Contraves, Switzerland)
Rapporteur : Alain DUPAS (CNES, France)

Session A_7
Chairman : Gregg MARYNIAK (SSI, USA)
Rapporteur : Géraldine NAJA (ESA)

Session A_8
Chairman : Hans-Peter RICHARZ (MBB-ERNO, FRG)
Rapporteur : Jean-Louis LAFON (BERTIN, France)

Session B_1
Chairman : Eveline GOTTZEIN (MBB, FRG)
Rapporteur : Claude POHER (CNES, France)

Session B_2
Chairman : Makoto NAGATOMO (ISAS, Japan)
Rapporteur : Jacques COLLET (ESA)

Session B_3
Chairman : Dieter KASSING (ESA)
Rapporteur : Anne SALETES (CNRS, France)

Session B_4
Chairman : Vladimir PRISNJAKOV (Dniepropetrovsk State University, USSR)
Rapporteur : Jean-François VALOBRA (MATRA, France)

Session B_5
Chairman : Helmut BEBERMEIER (Telefunken Systemtechnik, FRG)
Rapporteur : Lionel PELENC (Aérospatiale, France)

Session B_6
Chairman : Henri PFEFFER (ESA)
Rapporteur : Dominique VALENTIAN (SEP, France)

Session B_7
Chairman : William C. BROWN (Raytheon, USA)
Rapporteur : Georges FAILLON (Thomson, France)

Session B_8
Chairman : Richard BOUDREAULT (Technologies Aérospatiales, Canada)
Rapporteur : Marcel TOUSSAINT (Eurospace, France)

Poster Session
Chairman : Zéphyr TILLIETTE (CEA / DRN DMT, France)

SOCIÉTÉ DES INGÉNIEURS
ET SCIENTIFIQUES DE FRANCE

Commission "Électricité et Électronique"
Président : Mr Lucien DESCHAMPS

CONFERENCE

TUESDAY, AUGUST 27th, 1991 - 17.30

ÉCOLE SUPÉRIEURE D'ÉLECTRICITÉ (SUPELEC)
PLATEAU DE MOULON - 91190 GIF SUR YVETTE

by M. Frank P. DAVIDSON

Coordinator, Macro-Engineering Research Group,
MASSACHUSSETTS INSTITUTE OF TECHNOLOGY.
American Signatory of the 1957 Protocol
Founding The Channel Tunnel Study Group ;
and Vice-Chancellor, The American Society for Macro-Engineering

TOWARD PLANET-WIDE COALITIONS FOR LARGE-SCALE PROJECTS

While a "global approach" to the world's economy has almost become part of the conventional wisdom, one key question remains : are we preparing ourselves for-and are we selecting - the best available technological systems for this global economy - and without serious detriment to society and the environment ?

Can Buckminster Fuller's vision of a global electric power grid be reduced to practice ? If it can, would the resulting web of high voltage lines be comparable in cost - financial and environmental - with that of a transmission system based on microwave relay satellites ?

Will national and international institutions work out an operative consensus for the transfer of massive freshwater supplies to the African Sahel - or to the American Midwest ?

Will the statistics of automotive accidents (nearly five million hospitalizations per year for the planet) lead to the adoption and financing of improved technologies for guiding road traffic ?

How soon can there be commercial application of the 1985 demonstration on the Athletic Field of the Massachusetts Institute of Technology, of the physics of supersonic flight through an evacuated tube ? Is such a system thinkable for the high-speed Paris-Moscow link proposed by Mr. Gorbatchev at Strasbourg ? Will such a one-hour service be offered from Brest to Boston, or from Oakland to Osaka ?

A more comprehensive formation is needed for the training of engineer-managers for the public and private sectors alike, to select, prepare and manage the mega-projects of the next half-century. Requisite, also, is a more modern database on the options for and impacts of large-scale technical systems. Selection and planning of those mega-projects having genuine merit for the future will depend on a more mature design for engineer-management (business, government and research) and a more precise definition of the objectives sought.

PROGRAM

WEDNESDAY AUGUST 28th, 1991

ROOM A

8.45 9.15	OPENING CEREMONY

Rémy CARLE - Chairman of SEE

Jean RORET - Chairman of ISF

Hubert CURIEN - French Minister of Research and Technology.

The opening ceremony will be devoted to official welcome addresses.

LECTURE 9.15 10.00	OPENING LECTURE

I_0 SPS and the next century

Thierry GAUDIN - French Ministry of Research and Technology, Paris, France.

10.00 10.15	TECHNICAL PROGRAM PRESENTATION

Presentation of the technical program

Maurice CLAVERIE - CNRS, Paris, France
Chairman of the Scientific and Technical Committee of SPS 91 "Power from Space"

The aim of this symposium is to review the state-of-the-art of SPS and to project the future prospects for this concept.

The following topics will be covered :

1 - Global energy issue and societal challenge (2 sessions)

2 - Technology status - Transportation (1 session)

3 - Technology status - Power generation, conversion and storage (3 sessions)

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5 - Technology status - Systems (3 sessions)

6 - Extraterrestrial materials (1 session)

7 - Environmental issues (1 session)

8 - SPS development strategies (1 session)

9 - Demonstration projects (2 sessions).

10.30 12.45	OPENING SESSION

Co-chairmen - Maurice CLAVERIE (CNRS, France)
- Peter GLASER (AD Little, USA)

I_1 Human Exploration of Space and Power Development
Aaron COHEN, NASA, Houston, USA.

I_2 SPS interest and studies in USSR
Vladimir PRISNYAKOV, Dniepropetrovsk State University, USSR.

I_3 New Earth 21 Action Program
Jun OKUMURA, MITI, Tokyo, Japan.

I_4 GSEK - Global Solar Energy Concept.
Johann SPIES, MBB, ERNO, Bremen, FRG.

I_5 Energy Crisis and SPS for third world future
Rashmi MAYUR, Global Futures Network, Bombay, India.

12.45	END OF THE OPENING CEREMONY

WEDNESDAY AUGUST 28th, 1991

ROOM A

SESSION A1

14.15
16.00

GLOBAL ENERGY ISSUE (1)

Chairman : Arnaldo ANGELINI (ENEL, Academia dei Lincei, University of Rome, Italy)
Rapporteur : Christian VERIÉ (CNRS, France)

A1.1 Satellite Power Systems - Promise and Perspective.

A.R. MARTIN - AEA Technology, Culham Laboratory Abingdon, Oxon, UK.

A1.2 Terrestrial and space power systems: Life - cycle energy considerations.

D.R. CRISWELL - University of Houston, Houston, USA.

A1.3 Countermeasures for mitigating the effects of global environment changes.

L. M. JENKIS - NASA Johnson Space Center, Houston, USA.

A1.4 Solar Power Satellites: Energy source for the greenhouse century?

M.I. HOFFERT, S.D. POTTER, M.N. KADIRAMANGALAM, F. TUBIELLO - New York University, New York, USA.

A1.5 Energy in Asean: an outlook into the 21st century.

A. ARISMUNANDAR, P. DUPUIS - Ministry of Mines and Energy, Jakarta, Indonesia.

ROOM B

SESSION B1

14.15
16.00

SPS DEMONSTRATION PROJECTS (1)

Chairman : Eveline GOTTZEIN (MBB, FRG)
Rapporteur : Claude POHER (CNES, France)

B1.1 Rocket experiment METS - Microwave Energy Transmission in Space.

N. KAYA - Kobe University, Kobe, Japan.
H. MATSUMOTO - Kyoto University, Kyoto, Japan.
R. AKIBA - Institute of Space and Astronautical Science, Kanagawa, Japan.

B1.2 Demonstration of microwave power transmission in space.

K. CHANG, A.D. PATTON, M.O. KENNEDY, F.E. LITTLE, M.A. POLLOCK, K.A. HUMMER, J.C. Mc CLEARY, B.S. WEI, A.M. BROWN, J.O. Mc SPADDEN - Texas A & M University, College Station, USA.

B1.3 Experimental Radiation cooled magnetrons for space.

W.C. BROWN - Raytheon, Waltham, USA.
M. POLLOCK - Texas A & M University, College Station, USA.

B1.4 An evolutionary satellite power system for international demonstration in developing nations.

M. NAGATOMO - Institute of Space and Astronautical Science, Sagamihara, Japan.
I. KIYOHIKO - Hokkaido University, Sapporo, Japan.

B1.5 Design considerations for the "SPS 2000" ground segment.

P.Q. COLLINS - The Management School, London, UK.

WEDNESDAY AUGUST 28th, 1991

ROOM A

SESSION A2

16.30
18.30

GLOBAL ENERGY ISSUE AND SOCIETAL CHALLENGE (2)

Chairman Pr ARISMUNANDAR (Ministry of Mines and Energy, Indonesia)
Rapporteur : François MOISAN (AFME, France)

A2.1 Energy development and environment: What about solar energy in a long term perspective?

B. DESSUS - CNRS, Paris, France.
F. PHARABOD - MRT, Paris, France.

A2.2 A different race: Global Rural Electrification, Market niches, the Third World as a starting place for SPS.

R.S. LEONARD - Ad Astra, Santa Fe, USA.

A2.3 The Nuclear Power Satellite (NPS) - Key to a sustainable global energy economy and solar system civilization.

J.A. ANGELO Jr. - Science Applications International Corp., Melbourne, USA.
D. BUDEN - Idaho National Engineering Laboratory, Idaho Falls, USA.

A2.4 Global space fusion energy.

L.A. LATYSHEV - Moscow Aviation Institute, Moscow, USSR,
N.N. SEMASHKO - Moscow Power Engineering Institute, Moscow, USSR.

A2.5 A method for utilities to assess the SPS commercially

P.Q. COLLINS, R. TOMKINS - The Management School, London, U.K.

A2.6 Legal aspects of the use of SPS.

F. NORDLUND - Institut de Droit Aérien et Spatial, Montréal, Canada.

FORUM

18.45
19.45

FREE OPINION FORUM

The complete list of communications of this forum will be available at the begining of the symposium.

ROOM B

SESSION B2

16.30
18.30

SPS DEMONSTRATION PROJECTS (2)

Chairman : Makoto NAGATOMO (ISAS, Japan)
Rapporteur : Jacques COLLET (ESA)

B2.1 The global solar energy concept "1 MW Demonstration Mission".

H.P. RICHARZ - MBB/ERNO, Bremen, FRG.

B2.2 A feasibility study of Power Supplying Satellite (PSS).

H. MATSUMOTO - Kyoto University, Kyoto, Japan.
N. KAYA - Kobe University, Kobe, Japan.
S. KINAI, T. FUJIWARA - Nissan Motor Co., Tokyo, Japan.
J. KOCHIYAMA - Rocket System Corp., Tokyo, Japan.

B2.3 Small-scale space power station: Feasibility and usage prospects.

Y.A. MOZJORINE, V.P. SENKEVICH, A.D. KOVAL, E.A. NARIMANOV - TzNIIMash (Research Institute of Machine Bulding), Kaliningrad, USSR.

B.4 The IGRE's 100 kilowatt demonstration project.

R.S. LEONARD - Ad Astra, Santa Fe, USA.

THURSDAY AUGUST 29th, 1991

ROOM A

LECTURE

8.30
9.15

PLENARY LECTURE

I_6 Economic viability of using the Moon to supply energy to Earth.

Ivan BEKEY - National Space Council, Washington, USA.

SESSION A3

9.15
11.15

EXTRATERRESTRIAL MATERIALS

Chairman : Ivan BEKEY (National Space Council, USA)
Rapporteur : Gilbert PAYAN (Ministère de la Recherche et de la Technologie, France)

A3.1 Nonterrestrial resources for solar power satellite construction.

G.E. MARYNIAK, - Space Studies Institute, Princeton, USA.

A3.2 Economic impact of using lunar resources to build SPS systems.

R.S. LEONARD - Ad Astra, Santa Fe, NM, USA.

A3.3 The Moon as a source of energy for terrestrial use.

H.P. DAVIS - Davis Aerospace Company, Canyon Lake, USA.

A3.4 Construction materials for an SPS constellation in highly eccentric Earth orbit.

J.S. LEWIS - University of Arizona, Tucson, USA.

A3.5 ^{3}He for Fusion Power: The Willie Sutton Principle.

J.S. LEWIS - University of Arizona, Tucson, USA.

A3.6 Results of analyses of a lunar-based power system to supply Earth with 20,000 GW of electric power.

D.R. CRISWELL - Cis - Lunar Industries, Houston, USA.
R.D. WALDRON - Hacienda Heights, USA.

A3.7 Economics analyses of lunar resources for solar power satellies.

G.R. WOODCOCK -Boeing Aerospace & Electronics, Huntsville, USA.

ROOM B

SESSION B3

9.20
10.55

TECHNOLOGY STATUS: POWER GENERATION, CONVERSION AND STORAGE (1)

Chairman : Dieter KASSING (ESA)
Rapporteur : Anne SALETES (CNRS, France)

B3.1 Novel high efficiency multispectral photovoltaic structures for solar energy conversion in space.

Ch. VERIE, A. SALETES, B.BEAUMONT, J.C. GUILLAUME, M. LEROUX, A. LEYCURAS, A.FREUNDLICH, P. GIBART - Laboratoire de Physique du Solide et Energie Solaire, CNRS, Sophia Antipolis, France.
L. DESCHAMPS - EDF-DER, Clamart, France.

B3.2 Electronic materials for solar cells.

H.F. MATARÉ - International Solid State Electronics Consultants, Los Angeles, USA.

B3.3 Radiation-resistant high-efficiency concentrator solar cells for SPS.

V. POULEK - Czechoslovak Academy of Sciences, Praha, Czechoslovakia.

B3.4 Prospects of application of solar arrays with concentrators on near-Earth orbits.

A.S. KOROTEEV, A.M. KOSTYLEV, V.S. TVERSCOY - The Scientific-Research Institute of Thermal Processes, Moscow, USSR.

B3.5 Solar photovoltaic efficiency of structures on the ternary II-VI compounds.

E. BUZANEVA - Kiev University, Kiev, USSR.
E. CZARNECKA-SUCH - Jagellonian University, USSR.
S. RUMYANTSEVA - Moscow Research Institute Submicron, Moscow, USSR.

THURSDAY AUGUST 29th, 1991

ROOM A

SESSION A4

11.35
12.30

ENVIRONMENTAL ISSUES

Chairman : Anthony R. MARTIN (AEA Technology, UK)
Rapporteur : Michel HORS (Commissariat Général au Plan, France)

A4.1 The Environmental impact of SPS: A social view.

L.P. LEHMAN, G.E. CANOUGH - ExtraTerrestrial Materials, Endicott, USA.

A4.2 The Environmental benefits of Solar Power Satellites.

R. S. LEONARD - Ad Astra, Santa Fe, USA.

A4.3 Satellite Power System (SPS) space debris management strategies and technologies.

J.A. ANGELO, Jr. - Science Applications International Corp., Melbourne, USA.
T.E. ALBERT - Science Applications International Corp., Clearwater, USA.

ROOM B

SESSION B4

11.15
12.30

TECHNOLOGY STATUS: POWER GENERATION, CONVERSION AND STORAGE (2)

Chairman : Vladimir PRISNJAKOV (Dniepropetrovsk State University, USSR)
Rapporteur : Jean-François VALOBRA (MATRA, France)

B4.1 Different space electrochemical conversion and storage systems.

G. GAVE - CNES - TE/AE/SE/AC, Toulouse, France.

B4.2 High power conditioning for space applications.

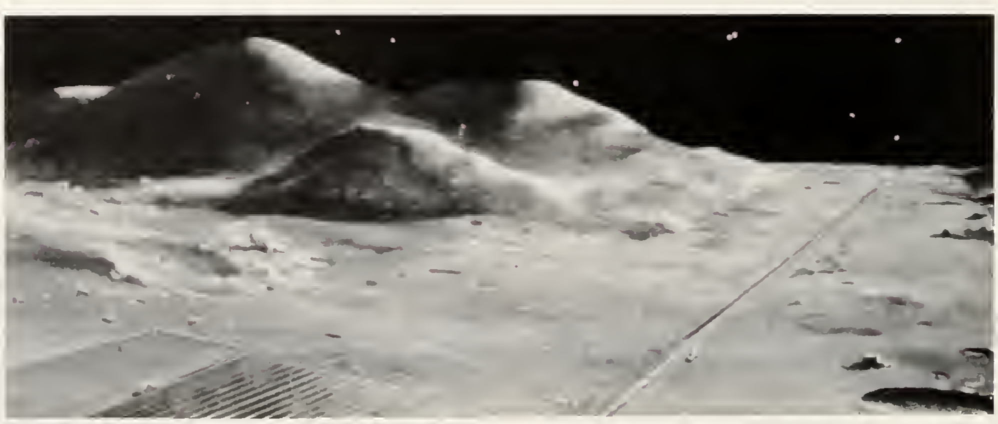
A. CAPEL - Alcatel Espace, Toulouse, France.
D. O'SULLIVAN - European Space Agency ESTEC, Noordwijk, Netherlands.

B4.3 Preliminary Plan for a 20 kW_e space solar "gyro-réacteur".

B. BAILLY DU BOIS, Paris, France.

B4.4 Optimization of Stirling and Ericsson cycles by solar radiation.

V. BÄDESCU, Polytechnic Institute of Bucarest, Romania.



Using lunar materials

THURSDAY AUGUST 29th, 1991

ROOM A

SESSION A5

14.00
15.45

TECHNOLOGY STATUS:
SYSTEMS (1)

Chairman : Frederick A. KOOMANOFF (DOE, USA)
Rapporteur : Michel DUCHET (LASERDOT, France)

A5.1 The impact of technology advances upon Satellite Power Systems.

A.R. MARTIN, V.K. THOMPSON - AEA Technology, Culham Laboratory, Abingdon, Oxon, UK.

A5.2 On some new principles of SPS design.

V.A. CHEREPENIN, B.M. PARAMONOV - Institute of Radioengineering & Electronics, Moscow, USSR.

A5.3 Integrated Solar Power Satellites: An approach to low-mass space power.

G.A. LANDIS, R.C. CULL - NASA Lewis Research Center Cleveland, USA.

a5.4 Future aera for SPS: "Donor-Acceptor" type power supply system for isolated and mobile consumers.

A. CHIGIREV - "Energocetproject", Moscow, USSR.

a5.5 Beam power options for the Moon.

E.H. FAY, M. STAVNES - Sverdrup Technology, Brook Park, USA.
R.C. CULL - NASA Lewis Research Center Cleveland, USA.

ROOM B

SESSION B5

14.00
15.45

TECHNOLOGY STATUS:
POWER GENERATION ,
CONVERSION AND STORAGE (3)

Chairman : Helmut BEBERMEIER (Telefunken Systemtechnik, FRG)
Rapporteur : Lionel PELENC (Aérospatiale, France)

B5.1 Five axes magnetic bearings turboalternator.

D. VALENTIAN - SEP, Vernon, France.

B5.2 Developing space power Brayton system with solar heat input - Research of working process of high temperature latent heat storage system.

V.F. PRISNJAKOV, I.N. STATSENKO, A.I. KONDRATJEV, V.L. MARKOV, B.E. PETROV, V.A. GABRINETS - State University, Dniepropetrovsk, USSR.

B5.3 A high-temperature solar receiver for space power.

A.T. MATTICK, K.A. Mc FALL - University of Washington, Seattle, USA.

B5.4 Solar dynamic power generation system.

S. VALENTINI, G. TUNINETTI - Ansaldo, Italy.

B5.5 Multicomponent liquid-metal coolants with regulated properties for space nuclear reactor-generator of big orbital station.

D.N. KAGAN - Institute for High Temperatures of USSR Academy of Sciences, IVTAN, Moscow, USSR.

THURSDAY AUGUST 29th, 1991

ROOM A

SESSION A6

16.15
18.20

TECHNOLOGY STATUS: SYSTEMS (2)

Chairman : Marco BERNASCONI (Contraves, Switzerland)
Rapporteur : Alain DUPAS (CNES, France)

A6.1 Magnetically inflatable SPS with energy storage capability.

M. EHSANI, O. BILGIC, A.D. PATTON - Texas A & M University, College Station, USA.

A6.2 Application of the concept of inflatable and rigidifiable structures to large space power stations.

P. COMTE, M. FERRONNIERE, C. MARCHAL - Association Internationale Arsat, Paris, France.

A6.3 Modeling of the development and infrastructure of solar electric power stations.

I. KURKIN, D. SEVRUK, D. SIDOROV, M. KUKOLEV, V. GORCHAKOV - Moskow Aviation Institute, Moscow, USSR.

A6.4 The complexation method of energy generation and angular motion control systems for space solar energy station concept.

V.G. KONOV, V.S. MANUILOV, U.V. PRISCHEPA, S.V. SHENDEREY - Leningrad Air-Space Ecology Centre "ECOS-CONVERSIA", Leningrad, USSR.

A6.5 SPGD: A central power system for space.

R.D. WIDRIG - Pacific Northwest Laboratory, Washington, USA.

ROOM B

SESSION B6

16.15
18.20

TECHNOLOGY STATUS: TRANSPORTATION

Chairman : Henri PFEFFER (ESA)
Rapporteur : Dominique VALENTIAN (SEP, France)

B6.1 Prospects for inexpensive space transportation.

R.C. RICHARDSON - High Frontier, Arlington, USA.

B6.2 SPS transportation requirements: which launch system?

R.J. HANNIGAN - CREST - Ecole Polytechnique, Paris, France.

B6.3 The plasma launchers for SPS.

B.A. OSADIN - All-Union Institute for Electromechanics, Moscow, USSR.

B6.4 A comparison of a conventional launch system vs. externally supplied vehicles for installation and maintenance of solar power satellites.

K. LÖTZERICH - DLR, Koeln, FRG.

B6.5 Earth based microwave power beaming to interorbital (LEO to and from HEO and GEO) electrically propelled transport vehicles.

O.E. MAYNARD, J.M. HOWELL, W.C. BROWN - Raytheon, Sudbury, USA.

FRIDAY AUGUST 30th, 1991

ROOM A

SESSION A7

8.30
10.15

DEVELOPMENT STRATEGIES

Chairman : Gregg MARYNIAK (SSI, USA)
Rapporteur : Géraldine NAJA (ESA)

A7.1 A research program for the planning of energy transmission systems through microwave beams, and evaluation of the related environmental impact.

A.M. ANGELINI - ENEL - Academia dei Lincei, University of Rome "La Sapienza", Rome, Italy.
P. BERNARDI, G. D'INZEO - University of Rome "La Sapienza", Rome, Italy.
F. FILIPPONE - Elettronica S.p.A., Rome, Italy.

A7.2 Energy transmission in space: an enabler technology.

M. TOUSSAINT - Eurospace, Paris, France.

A7.3 Broad-based space solar power advocacy

W.N. AGOSTO - Lunar Industries, Houston, USA.

A7.4 SPS technology development strategy in the context of the space exploration initiative.

C. POHER - CNES, Cannes La Bocca, France.

A7.5 Space Solar Power Program (SSPP) design project for the international space university 1992 summer session in Kitakyushu, Japan.

G.E. MARYNIAK - Space Studies Institute, Princeton, USA.
T.B. HAWLEY - International Space University, Cambridge, USA.

ROOM B

SESSION B7

8.30
10.15

TECHNOLOGY STATUS: TRANSMISSION (1)

Chairman : William C. BROWN (Raytheon, USA)
Rapporteur : Georges FAILLON (Thomson, France)

B7.1 The Magnicon as a highly efficient, high power, high frequency source for space power beaming.

W. MANHEIMER, S. GOLD - Naval Research Laboratory, Washington, USA.
Y. SEO - FM Technology, Springfield, USA.

B7.2 Cyclotron-wave converter for SPS energy transmission system.

V.A. VANKE, V.L. SAVVIN - Moscow State University, Moscow, USSR.

B7.3 Microwave sources for power transmission in space.

M. FIRMAIN et al.- Thomson Tubes, Vélizy, France.

B7.4 Antenna synthesis for the SPS microwave transmission system.

V.A. VANKE, A.A. ZAPOROZHETS, A.V. RACHNIKOV - Moscow State University, Moscow, USSR.

B7.5 An inland rectenna using reflector and circular microstrip antennas

K. ITOH, Y. OGAWA - Hokkaido University, Sapporo, Japan.

FRIDAY AUGUST 30th, 1991

ROOM A

SESSION A8

10.45
12.30

TECHNOLOGY STATUS:
SYSTEMS (3)

Chairman : Hans-Peter RICHARZ (MBB-ERNO, FRG)
Rapporteur : Jean-Louis LAFON (BERTIN, France)

A8.1 Problems experienced by man when constructing giant structures in space.

C. A. TIMSIT - MEDISPACE, Paris, France.

A8.2 The effect of human productivity in space construction on SPS transportation costs.

R.H. MILLER - Massachussetts Institute of Technology, Cambridge, USA.

A8.3 Solar-pumped solid state lasers for space - Space power transmission.

U. BRAUCH, H. OPOWER, W. WITTWER, J. MUCKENSCHNABEL - DLR, Stuttgart, FRG.

A8.4 A lightweight focusing reflector concept for space power applications.

T. WALLACE, R. W. BUSSARD - Arco Power Technologies, Washington, USA.

A8.5 The application of electric propulsion to powersat demonstrators.

D. VALENTIAN - SEP, Vernon, France.

ROOM B

SESSION B8

10.45
12.30

TECHNOLOGY STATUS:
TRANSMISSION (2)

Chairman : Richard BOUDREAULT (Technologies Aérospatiales, Canada)
Rapporteur : Marcel TOUSSAINT (Eurospace, France)

B8.1 35 and 94 GHz rectifying antenna systems.

P. KOERT, J. CHA, M. MACHINA - ARCO Power Technologies, Washington, USA.

B8.2 Frequency range analysis for power transmission by electromagnetic beam.

V. RYBAKOV, A. SMAKHTIN - Moscow Aviation Institute, Moscow, USSR.

B8.3 The way of VHF power transmission from the solar energy space installation by generating videoimpulses.

S.V. SHENDEREY, V.G. KONOV - Leningrad air-space ecology centre "ECOS-CONVERSIA", Leningrad, USSR.

B8.4 Space power supply network using laser beams.

M. DUCHET, L. CABARET, A. LAURENS, J.C. de MISCAULT - Laserdot, Marcoussis, France.
M. TOUSSAINT - EUROSPACE, Paris, France.
J.P. GEX - Sylarec, Marcoussis, France.

B8.5 High precision laser pointing experiment for power transmission.

H. JÖRCK - MBB Deutsche Aerospace, Munich, FRG.

FRIDAY AUGUST 30th, 1991

ROOM A

LECTURE

14.00
14.45

PLENARY LECTURE

I_7 **The Solar Power Satellites option re-examined**
Peter GLASER - AD LITTLE, Cambridge, USA.

14.45
16.00

ROUND TABLE

Leading international experts will discuss on the following subject :
. **Towards an International cooperation for SPS evaluation and development: Objectives? How?**

16.00
16.30

CONCLUSION

Synthesis of the SPS 91 "Power from Space" Symposium.

Lucien DESCHAMPS - EDF/SEE, Paris, France.

16.30

SPS 91 AWARD

"SPS 91" prize will be awarded to authors whose paper, through its relevance as well as the quality of the presentation, deserves special recognition.

The Chairmen of the Organizing Committee and of the International Scientific and Technical Committee will hand over the SPS AWARD at the end of the Symposium.

From WEDNESDAY AUGUST 28th morning to FRIDAY AUGUST 30th evening

ROOM C

POSTER SESSION SPACE POWER

Chairman : Zéphyr TILLIETTE (CEA/DRN DMT, France)

C1.1 The SPS economic and ecological consequences.

A. BORISENKO - Kiev's Polytechnical Institute, Kiev, USSR.

C1.2 Six port junctions for the control of phased array antennas on microwave power satellites.

F.M. GANNOUCHI, R.G. BOSISIO - Laboratoire de micro-ondes, Ecole Polytechnique de Montréal, Canada.

C1.3 Space nuclear power system studies in France.

F. CARRE, J. DELAPLACE, E. PROUST, Z. TILLIETTE - C.E.A. DRN-CEN Saclay, Gif-sur-Yvette, France.

C1.4 Increasing the power of microwaves using concentrated sunlight.

J. ESSANDOH-YEDDU, Ministry of Fuel and Power, Accra, Ghana.

C1.5 Space Solar Power Program (SSPP) design project for the international space university 1992 summer session in Kitakyushu, Japan.

G.E. MARYNIAK - Space Studies Institute, Princeton, USA.
T.B. HAWLEY - International Space University, Cambridge, USA.

C1.6 Economics analyses of lunar resources for Solar Power Satellites.

G.R. WOODCOCK, Boeing Aerospace & Electronics, Huntsville, USA.

C1.7 Liquid Metal Magnetohydrodynamic (LMMHD) converter for space power system.

A. ALEMANY, Ph. MARTY, J.P. THIBAULT, Institut de Mécanique de Grenoble, Grenoble, France.

C1.8 Power from Space in very natural way.

V.S. SYROMIATNIKOV, NPO Energia, Moscow, USSR.

C1.9 Mission to save planet Earth.

J. SVED & P.W. SHARP, ERNO, Bremen, FRG.

C1.10 The himalayan hydro machine and space transmission power systems : An asian dream of 21st century.

M. ADMODDIE, Bombay, India.

C1.11 Project Phoenix.
Fire Replaced: Solar Power and Global Warming.

C. OWEN, H. KAVINSKY - Illinois Institute of Technology, Chicago, USA.

C1.12 Inflatable Hose Structure Parabolic Antenna for Space Applications.

A. GORLOV - Northeastern University, Boston, USA.
I. PALLEY, A.J. SIGNORELLI - Allied Signal, USA.

C1.13 About the possibility of power supply of spacecrafts by ground laser beams.

Y.I. KRUZHILIN - Astrophysica, Moscow, USSR.

C1.14 Constructions and ground testing of large high precision space structures.

E. MEDZMARIASHVILI, A. IAKOBASHVILI, G. BEDUKADZE - Georgian Technical University, Tiblisi, USSR.

C1.15 The legal regime of the Moon regarding the exploitation of natural resources.

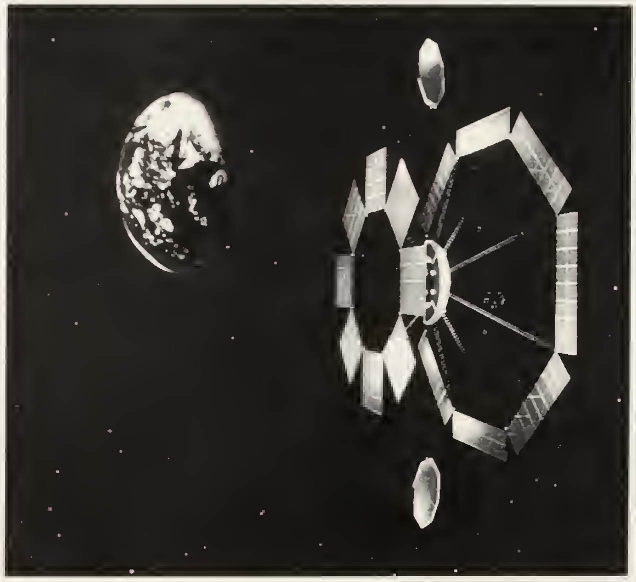
C. KOENIG - University of Marburg, Marburg, FRG.

C1.16 Topaz optimal source of electrical energy for advanced civil space applications.

G.M. GRYAZNOV - NPO "Krasnaya Zvezda", Moscow, USSR.

C1.17 Extraterrestrial resources: A metallogenical typology.

A. GIANNONI - CREST - Ecole Polytechnique, Paris, France.



SPS (Project Phoenix)

TEXTS OF COMMUNICATIONS

SPS 91

I$_0$ SPS and the next century

Thierry GAUDIN - French Ministry of Research and Technology, Paris, France

SUMMARY

More than 12 billions of humans could live on this planet in the next century without severe physical constraints on raw materials, energy, food, environment, etc., with the prerequisite of organizational changes. For them SPS might be an importantant source of clean and abundant energy, and possibly a gate to the space colonization to be expected.

RESUME

Plus de 12 milliards d'hommes pourraient habiter cette planète au siècle prochain sans limitations physiques graves (matières premières, énergie, nourriture, environnement, etc.), moyennant des changements organisationnels. Les SPS representeront peut etre pour eux une source importante d'énergie propre et abondante, et une voie d'accès à la très probable colonisation de l'espace.

INTRODUCTION

The Center for Prospective of the French Ministry of Research and Technology issued end of 1990 a book entitled " 2100, récit du prochain siècle " (2100, tale of the next century), to which several hundreds of research workers took part. The present paper emphasizes some of the features of this study which show that SPS may have a considerable importance for the future of mankind.

All along the elaboration of the book it appeared that the conclusions of the " Club of Rome " were too pessimistic. Due to reasonably predictable advances of science and technology, it should be possible that more than 12 billions of humans live on Earth without severe physical constraints. Raw materials, energy, food, environment problems should be solved, the most delicate, but also solvable question, being the containment of megapole growth. Of course some organizational changes are a prerequisite for the solution of material problems: this is true in particular for education, which calls for a worldwide effort.

Regarding energy, two constraints appear: According to our scenario, consumption of fossil fuels will be limited, for environmental reasons; use of atomic energy will be restricted to those countries which are in the position of limiting its risks to an acceptable value. Therefore two directions must from now on be considered with most attention: energy savings have to be encouraged all around the world, fortunately coinciding in many cases with global economic savings, as can be already shown in the cases of housings and cars for instance. Use of renewable energy, and primarily of solar energy, has to be developped, and corresponding R&D ranks among world priorities. SPS development is therefore a task whose interest should in no case be underestimated.

A special attention should be brought to the construction of SPS from extraterrestrial, and particularly lunar material. This way seems economically promising. But more generally the recourse to space

for energy, raw materials, and even for the setttlement of our species seems to be one of the strong features of our destiny.

DEMOGRAPHY IN THE NEXT CENTURY

It is generally admitted that world population should grow in the next decades and reach a maximum around year 2100. The reason is that more and more countries are attaining the material and cultural level where their native population stops growing, then decreases. This has clearly happened in most western countries: all other parts of the world follow or will follow the same path, even if Africa at the present time does not show many signs of doing so.

As regards the maximum level of world population to be expected, it is difficult to mention anything else than a large range. United Nations estimated recently this range between 10 and 15 billions of people. Our own model gives a figure of 12 billions in 2100, with a peak of 12.5 billions in 2200., therefore inside the limits of United Nations expectations. It differs of other ones in that we take into consideration some migratory fluxes, and admit that the greenhouse effect will make habitable some northern parts of SIBERIA and ALASKA for instance, while causing some damages to seaside and southern countries. It must be noticed that both of these assumptions have little effect on the total world figure.

FOOD

The first question raised by demographic previsions is: how will those 12 billions or more humans be fed? Briefly speaking, the answer is: decently, provided they are educated.

As a matter of fact, all agricultural techniques exist or can be foreseen, which allow feeding such masses. But existing techniques are often ignored by those who should use them.

A good example of the ways to follow is the " green revolution ". American Ford and Rockefeller Foundations have launched in the sixties successful researches on rice and other cereals. Very productive and resistant varieties have been obtained. Then the corresponding know-how has been diffused, through instructors, in the villages of India and China, allowing to match the increase of population up to now.

More generally, new techniques of hybridization allow producing plants better resisting to cold temperatures, to sudden lack of water, but also to attacks of bacterias and viruses. Those plants may have also better contents of proteins, for instance, and be more abundant on a given cultivated area.

To progress further along those lines, great hopes can be placed in genetical engineering, i.e in techniques of modifying the collection of genes possessed by the plant. It is foreseen for instance that specific genes will be introduced in some vegetals, making them able to fix directly nitrogen from the air, with a double favourable result: No nitrogeneous fertilizer will be necessary, and therefore no pollution by nitrates will be feared.

Genetical engineering can similarly apply to animals. Introducing the genes of growth hormones will make animals larger. Other genes will give them flesh of a better quality, and a better resistance to all sorts of illnesses.

Proteins will also come abundantly from fish, which will more and more be produced in sea-farms; it must be noticed that salmon obtained that way is together excellent and relatively cheap. Algaes raised in the sea will help feeding cattle, with some varieties being praised by humans, either in natural form or combined in special dishes. Food industry should play an ever increasing role, combining for instance proteins of various natures (meat, fish, soja, wood, bacterias etc.) with other ingredients in order to create dishes of pleasant texture and taste.

All technical conditions will therefore be met to allow most parts of the world to be self-sufficient for their basic food to a large extent. Availability and quality of agricultural soils will be a less important problem than it is today, due to the development of hydroponic cultures, i.e. cultures without soil where nutrients of the plant are brought through water. Shortage of water in many regions will be prevented by intensive recycling of used waters after purifying them, often with the use of bacterias produced by genetical engineering. Later on desalinization techniques of seawater will contribute largely to sort water supply.

RAW MATERIALS

Many raw materials come from agriculture, such as rubber, cotton, wool etc. What we said for food materials is valid here: progress in quality and productivity can be expected from new techniques, in particular from genetical engineering. In addition products obtained by chemistry, the many polymers, will be continuously developed and possibly substituted to natural products, as happens since several decades.

Polymers are used as substitutes of many other products, and some of them will even compete with copper and aluminium for the conduction of electricity. They are themselves mainly derived from oil,

gas and coal. We shall treat those materials when discussing energy problems, but we can say now that chemical industry uses only a small part of their production, and should in the coming century have sufficient access to them without too many difficulties.

Other raw materials have their final use mainly in manufacturing industries. Three remarks lead to think that they should not cause deep concern of shortage: they can often be substituted, as we just saw; they are and will be more and more recycled, as can be observed in the automobile industry where some builders make it a policy ; and finally the manufactured objects are lighter and lighter. Let us detail that last point. A glass bottle which was weighing 170 grams in 1974 weighs only 95 grams now. All mechanical products, from car to freezer, have beeen equally weigh-watchers ! Main reasons for those successful cures are progress in materials and advances in calculation. Those progresses will not stop.

ENVIRONMENT

The most common fear about environment concerns the greenhouse effect, mainly caused by CO_2 produced by combustion of fossil fuels, and inducing " global warming " . Measures can be taken against it in the frame of energy policy, but their effect will be slow, and it is reasonable to expect an increase in atmospherical temperature for the fifty years to come, more important in higher than in lower latitudes. Two consequences will result: thermal dilatation of seawater and melting of glaciers will increase sealevel, which means submersion of large coastal regions, in Indonesia, Bangladesh or Egypt for instance, unless some enormous dikes are built. And territories like Sahel will be still more desertified, while on the other hand, as we already mentioned it, very large northern parts of Canada and Siberia will become suitable for cultivation and settlement. Global result will be mainly a displacement of populations.

The problem is serious but we are at least equally preoccupied by deforestation. Forests retain rain water, then release it progressively in the atmosphere, contributing for a large part to climatic equilibria. It is very hard to predict which climatic changes could happen if the present trend to deforestation, in particular in tropical countries, is not stopped and reforestation undertaken. It will certainly be a matter of international negociations, Amazonia being presntly in first line.

The destruction of the layer of ozone is also a widely shared concern, but we think that conscience of its dangers will be sufficiently spread so that adequate measures be taken, such as limitation of the use of CFC already decided by many countries. Other industrial nuisances include acid rains or rejection of heavy metals like lead or mercury. They can be technically harnessed. Politically we must distinguish between developed countries , where the most efficient pressure seems to lie in taxing the polluters, and less rich countries, which must be helped in their development by richer ones in such a way that pollution is limited. A report of the World Commission on Environment and Development shows that this development policy is feasible.

MEGAPOLES

The growth of megapoles may be the toughest problem associated with the increase of population: this growth is amplified by the disparition of many agricultural farms which are no longer competitive. It is already quite visible in developing countries where enormous towns like Mexico, Bombay or Sao Paulo are not especially pleasant to live in. In particular a large part of the population, recently arrived from the country and quite uneducated, lives like in a jungle in quarters where the police does not come. Similar situations can be observed, though to a lesser extent, in large towns of industrialized countries. Extrapolation of this trend would lead to enormous social disorders.

However in many developed countries measures have been taken to limit the growth of megapoles. Middle towns are created or developed, connected with the megapole and between them by trains whose speed is continuously increasing. In the future this speed will still grow, and progress in telecommunications will allow people to work in or near their dwelling place a large part of the time, travelling to their office may be two or three days a week. Reduction of construction costs caused by new materials, automated methods of designing and building, etc. should also facilitate rebuilding of the worst parts of megapoles. As regards the " urban savages " the main prerequisite for their social integration is certainly, here also, education.

In developing countries, similar methods should progressively be employed, together with efforts to fix or bring back populations to land, by promoting appropriate local agricultural techniques, as we saw hereabove. This seems feasible, but will take decades, and many difficult situations are to be expected in the meantime.

ENERGY

In order to meet the requirements of environment and to avoid scarcity, energy policies must be carefully thought. The first urgency is to limit the consumption of fossil fuels (coal, oil and gas). They are responsible for greenhouse effect, but also for acid rains. One solution, applied in France on a large basis, is the construction of nuclear power stations, with major emphasis put on safety.

it can not be spread everywhere in the world, because safe construction and operation of these stations require certain levels of technical and organizational development, especially if one wants to face the risk, very small but not unreal, of an accident.

Energy saving is another appropriate answer with high potential. As a matter of fact it happens naturally: from economic reasons, for a given service, the consumption of energy is decreasing along the years. This is obvious for instance for cars or for houses. But it can be observed more generally for transportation, where rapid trains like TGV use far less electricity than slower ones and of course than planes they replace, for agriculture and for industry. In the case of industrial products like cars and houses, it is impressing to see how much the amount of energy necessary to manufacture their components and to assemble them has dropped in the last thirty years. There remain however still many overconsumptions of energy which will disappear in the decades to come under economic pressure, this pressure being often exerted by the governments through taxes or subsidies. It must be noted that developing countries will be able to use energy-saving techniques created by reacher ones.

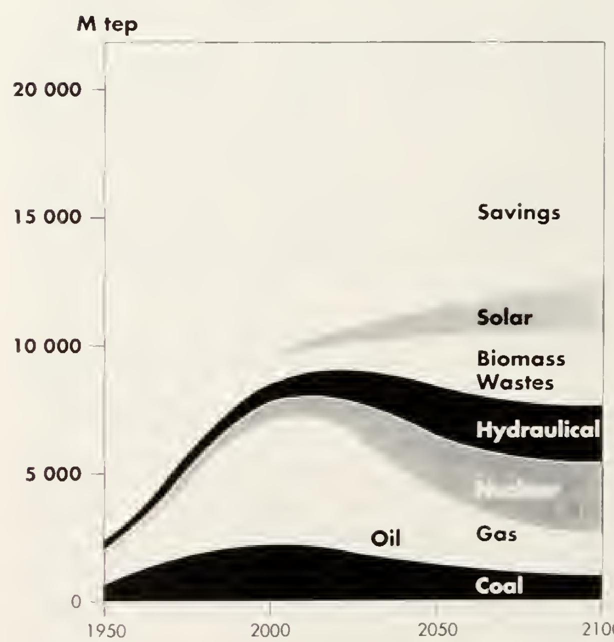
We come now to use of main renewable energy sources. Many potential hydroelectric sites, small or large, are not yet equipped. This is true in particular for the mountains of Andes and Himalaya. Equipping them will have the additional advantage of reducing floods. Biomass (wood and agricultural wastes) can supply fuels like ethanol without increasing the CO2 content of atmosphere, since new trees or plants can grow where this biomass has been removed for use. These clean motor fuels will compete with hydrogen produced by water electrolysis ; hydrogen is the cleanest conceivable fuel and should replace fossil fuels not only in motors of cars, planes or ships, but also in heating devices used in houses or factories.

Last, but not least, solar energy must be developed. It is competitive today in some areas for water heating, and in some sunny isolated points for electricity production. However the cost of photovoltaic cells will decrease and solar power stations of a large size will become competitive in such areas like northern Africa or Middle-East. In parallel we are expecting much from SPS. One of the main advantages we see in those plants is that the spatial part can be built and operated by rich nations, while the receiving ground part, the rectenna, may be built and operated by less industrialized countries: those countries are very often the ones where the use of nuclear energy does not seem appropriate. Moreover they may have a relative lack of water, and the rectenna does not require cooling water.

We believe that vigorous efforts of R&D must be made, on an international basis, to develop SPS, and especially SPS built from extraterrestrial materials. Building these stations from lunar material seems attractive from an economic and ecological point of view, but we are sensitive to another advantage of this method. It will speed up the process of space industrialization and we think that on the long run space will be an important source of raw materials for mankind: these materials, coming from moon or asteroids, will be used in space industry for production of power stations, satellites or transportation vessels, and progressively for the construction of space cities where in the future a large part of mankind might live.

N.B. A chart below shows the future of energy as we see it possible until 2100. It was too soon for distinguishing in detail between terrestrial and spatial solar energy. Fusion energy, if its feasibility is proved, might modify this chart.

World evolution of Primary energy sources



I₁ Human Exploration of Space and Power Development

Aaron COHEN - NASA, Houston, USA

ABSTRACT

This paper shows compelling reasons for mounting the U.S. Space Exploration Initiative, discusses the variables facing U.S. planners, and presents the developmental technologies that will be needed to support this initiative. World energy demands and the pressure of sustaining those needs have led to studying the use of lunar resources. The three more advanced technological approaches in the field of power generation presented include a geosynchronous-based Earth orbit solar power satellite system, a lunar-based solar power system, and the use of helium-3/deuterium fusion reaction to create a nuclear fuel cycle.

RESUME

Cette communication souligne les motivations essentielles pour la mise en oeuvre d'une Initiative Américaine d'Exploration de l'Espace; elle présente les alternatives offertes aux responsables américains et les développements technologiques nécessaires en soutien à cette initiative.

Les besoins énergétiques mondiaux futurs et la nécessité de satisfaire ceci ont conduit à étudier les perspectives des matériaux lunaires. Trois voies sont envisagées :

- centrales solaires spatiales en orbite géostationnaire de la Terre réalisées à partir de matériaux lunaires,
- centrales solaires installées sur la Lune,
- utilisation sur Terre d'Hélium 3 lunaire pour un cycle de fusion contrôlée He^3 - Deutérium.

Human Exploration of Space and Power Development

In the late 1980's, United States space policy began to emerge from the confusion and tragedy of the Challenger accident with a broader vision for the development of what John F. Kennedy called "this new ocean." Already on the table were a series of studies, fostered by the Apollo Program, which answered the age-old question and told us what the Moon was made of. These studies also suggested ways to benefit from this newfound knowledge. The report of the National Commission on Space in May 1986 said the country could prosper from a long-range program to become a more robust space-faring power, with exploration, resource development, and commercial investment stretching from the shores of Earth to beachheads on the Moon and Mars. This was followed in August 1987 by the Ride Report, in which scenarios for returning to the Moon, exploring Mars, and studying the ecosystem of the Earth were examined and assessed. The Annual Report to the NASA Administrator in 1988 further crystallized U.S. thinking that an expanded infrastructure in low Earth orbit could be the springboard for more advanced forays out and away from our home planet.

In July 1989 when the nation paused to reflect on the 20th anniversary of the first lunar landing, President Bush took these ideas and made them national goals as he committed the country to construction of permanent bases in low Earth orbit and on the Moon and, eventually, to the human exploration of Mars. At the President's direction, NASA undertook a 90-day study on how to implement this broader policy, which came to be called the Space Exploration Initiative, or SEI. Currently, a team known as the Synthesis Group, led by General Tom Stafford, is performing additional studies in this area, and the report is due in April 1991.

Of even longer duration is another field of study which arose in the 1970's with the first great throes of energy dependency. This field involved identifying scenarios for obtaining vast amounts of energy from the free-flowing well of the Sun's output, with a variety of space-based technologies. For almost 20 years, these studies have led us to consider huge solar power satellites, mass drivers, space platforms and antenna systems, and the launch and support vehicles necessary to carry out such large-scale endeavors. During the 1980's, these studies were supplemented with extensive space operations in nearly 40 flights of the reusable, first-generation Space Transportation System. Materials were tested, techniques were honed, and construction methods were demonstrated for the first time.

This paper will discuss how the U.S. Space Exploration Initiative opens new opportunities in these fields, and will offer a synthesis of the latest trends and techniques for tapping new energy resources while also achieving environmental benefits.

The Variables

The Space Exploration Initiative marks a fundamental shift in the U.S. approach to spaceflight. No longer limited to the technical and operational specifics of any one vehicle or any one mission plan, SEI will involve a

fleet of spacecraft and a stable of off-planet research laboratories and industrial facilities. Thus, many variables must be considered in defining the approach and selecting the methods for carrying out the President's goals.

The list of variables facing U.S. planners in the early 1990's begins with the mission requirements for SEI: what do we want to do, and how can we best achieve it? As those requirements come into focus, so does the schedule, which in turn will be structured around the nature and scope of international involvement in SEI. Also, the size and capabilities of our launch vehicles will influence mission design and schedule. In the process, a choice will be made between in-space assembly of large systems and direct transport to the surface of the Moon or Mars. The design and use of Space Station Freedom will be weighed against other spaceport designs or the concept of direct assembly. Will we need a spaceport in lunar orbit, for instance? We also must choose from a range of options for transporting people back and forth from the Moon and Mars, and for delivering cargo to our lunar and Martian outposts.

As we consider the mission requirements for Mars exploration, we must choose from a set of trajectories to the Red Planet, including methods known as Sprint, Split/Sprint, Opposition, Conjunction, and Venus Assist. Another variable is whether to mount the Mars missions as individual expeditions or build one mission upon the next in a more evolutionary fashion. Before we embark on either course, however, we must decide whether to send precursor or robotic missions to survey and assay Mars first.

The question of how to get to Mars, aside from what trajectories to choose, also must include a decision on chemical, electric, nuclear, or unconventional propulsion techniques. We must also consider aerobraking as an alternative to all-propulsion vehicles, and we must choose between expendable and reusable spacecraft.

As these and other options are explored, the list grows with other variables. Do we transfer propellants from tank to tank, or do we transfer the propellant tanks themselves? Do we choose open- or closed-loop life support? Do we commit to vehicles which carry passengers in a zero-gravity environment, or do we attempt to induce artificial gravity? Finally, as a gauge of our confidence and our capabilities, either we must choose to develop resources in situ, or we must plan to supply resources from the Earth.

With all of those variables in mind, the discussion today centers on a logical starting point: the size and design of the launch system. Several candidate designs are being considered for an Advanced Launch System, and many of these same variables will be eliminated once a choice is made. The most practical launch vehicle size will likely be in the 110 to 120 metric ton class. Studies show that a very robust heavy-lift launch vehicle will be required to support lunar base construction and the initiation of scientific and resource development projects. One such baseline plan for lunar exploration requires 200 metric tons of payload, including vehicles and propellant. A comparable Mars mission would require about 800 metric tons of materiel. The methods of deploying this mass can vary from launching directly from Earth in expeditionary fashion, to assembling spacecraft in low Earth orbit, to launching cargo and then humans.

Whatever method is chosen, I believe the President's exploration program ultimately will involve the following major elements:

1. A heavy-lift launch vehicle, primarily to boost large cargo shipments from the surface of the Earth to low Earth orbit;
2. A transfer vehicle, used initially for trips from low Earth orbit to lunar orbit, that can be uprated for journeys to and from Mars;
3. A descent/ascent vehicle, suitable for use on lunar missions and adaptable to Mars exploration;
4. Technology development programs in the fields of life support, propulsion systems, radiation protection, extravehicular activity systems, and expendable supplies;
5. A decision to aggressively utilize the growing science of in situ resource development on both the Moon and Mars.

There is no technology breakthrough on the horizon that will make the exploration initiative easy. There will be, however, a series of developmental efforts that will refine our technological means, making the task less costly, more reliable, and more efficient. Five of the technologies we need to support SEI, and therefore must develop most aggressively in this decade, are:

1. Closed-loop life support to reduce weight and logistical complexity;
2. Cosmic radiation protection for flight crews, and the ability to forecast and warn against cosmic radiation events;
3. Nuclear propulsion to reduce the long transfer time;
4. Aerobraking, which offers elegance and efficiency in reducing the weight of propellants and tankage;
5. Advanced power generation systems.

And if we are to make SEI less costly, more reliable, and more efficient, we must develop advanced extravehicular activity systems; experiment with novel structures (such as inflatable habitats); expand our operational envelope in the areas of guidance, navigation, and control; and most importantly, find solutions for the human body's physiological response to prolonged periods of weightlessness.

Energy and the Limits to Growth

Against this backdrop of our planning for space exploration looms a problem so large that it can be stated simply: our modern society has an insatiable demand for energy, and we are running out of it. And even if we can find it, we risk polluting our atmosphere as we use it. Energy needs are rising daily, and the pressure of sustaining this rising demand is turbulent, at best, both politically and economically and now environmentally. Our practical options are limited, at least in the near term, to burning more hydrocarbons in the form of coal and oil, thereby contributing to greenhouse warming by the release of carbon dioxide, or to expanding nuclear fission, with its own political limitations and environmental problems. Neither option is attractive, yet they are the only solutions available to us now.

Whether either option is even viable, in a larger sense, is brought into focus by our estimates of future requirements. By the year 2030, that requirement will be enormous. Some experts say that our power consumption will increase, conservatively speaking, by 5,000 gigawatts over the next 40 years. Putting this another way, we will, as a planetary society, go from using 2 trillion barrels of oil in 1990 to 6 trillion barrels of oil in 2030. If we meet this demand by burning hydrocarbons, we will pose an even graver risk to our fragile environment.

These limits to the growth and extension of humanity on Earth have become all too apparent in a generation. Perhaps it is our great good fortune that this was the same generation that has witnessed the dawn of the Space Age. The depletion of Earth's resources and the fouling of our environment are now seen as threats to civilization, but at the same time we can see how the resources of space can be used to greatly reduce this threat in the next century. Nowhere is this more so, or more central to the possibilities of space development, than in the creation of new energy resources.

We are already using the resources of space in a limited way. Solar energy is gathered in space and used to power our satellites and space stations, for example. The cost is quite high, however, and the attainable power levels are low. SEI will require us to move beyond these limited applications. In SEI, the first use of resources will be straightforward--planetary surface materials will be used as shielding against cosmic radiation, eliminating the need to bring shielding material from the Earth. Likewise, propellants distilled from rocks, soil cryosphere, or the Martian atmosphere can offset more than half of the propellant that would otherwise have to be transported from Earth. For SEI to succeed, however, and for a lunar base to expand and flourish, these straightforward approaches will soon give way to more advanced technologies, especially in the field of large-scale power generation, and three such technological approaches are discussed here.

The Three Approaches

The first approach would use lunar raw materials to construct a large solar power satellite in geosynchronous Earth orbit. The solar power satellite would be capable of beaming thousands of megawatts of power to Earth continuously day or night. (A thousand megawatts is approximately equivalent to the amount of solar energy falling on a square kilometer of the Earth during the middle of a cloudless day.) The use of lunar material would reduce up to 50-fold the number of launches required from the Earth to construct such a satellite. This system will be referred to as the geosynchronous-based Solar Power Satellite, or the SPS.

The second approach would involve a similar system for gathering solar energy and beaming it to receptors on Earth, but would be built on the lunar surface. This lunar-based system, built from the raw materials at hand, also would significantly reduce the number of launches required to supply the effort from Earth.

A third approach may offer the greatest breakthrough potential, but will depend on both space-based and terrestrial technology development programs. Our studies of the Moon have shown that an isotope rare to the Earth, helium-3, exists in great quantities (but low concentrations) on the lunar surface. More recent studies have shown that helium-3 has great promise as a fuel for nuclear fusion reactions. If such a breakthrough could be achieved, estimates show that just 20 tons of helium-3 mined on the Moon could provide an energy output equal to the current annual electrical consumption of the United States.

The Solar Power Satellite

From 1977 to 1980, the Department of Energy (DOE) and NASA jointly participated in a concept development and evaluation program which made a broad, end-to-end assessment of a geosynchronous Earth orbit (GEO) solar power satellite system that could convert solar energy collected in space into electrical energy for use on Earth. In the reference systems developed for the assessment, each satellite had a collector made up of solar silicon cells with an area of 50 square kilometers. The mass of each satellite was estimated to be 50,000 tons. The design converted solar energy into direct current electrical energy, and included a microwave subsystem which used klystrons for conversion of the direct current radio frequency energy, and a 1-kilometer-diameter phased-array transmitting antenna to beam microwave energy to Earth at 2.45 gigahertz.

On Earth, a 75-square-kilometer rectifying antenna would receive the microwave energy, convert it back to electrical energy, and insert it into a terrestrial utility grid. Each system would provide 5 gigawatts of output on the ground, which is approximately the capacity of five conventional nuclear power plants.

The reference concept required the development of a launch system which had a single mission delivery capability of about 425 tons to low Earth orbit (LEO). This payload of satellite components, building materials, construction equipment, and expendable supplies would be delivered to a LEO staging base. A transfer system using electric propulsion with ion engines would take the cargo from LEO to GEO. Once at GEO, the transfer vehicle would dock with a 6,400-ton construction base and unload its cargo. The base would have a crew of about 400 people who could build an SPS in about 6 months. Following checkout of the satellite system, the base would be moved on to another point in GEO where another satellite would be built. The analysis in this study was based on construction of two solar power satellites a year for 30 years.

In such a plan, the heavy-lift requirement from Earth to LEO would be eight 425-ton cargo shipments per week, or about 400 per year. Personnel would shuttle back and forth from the Earth about 32 times each year on ships capable of carrying 75 to 80 passengers one-way. The crew at the LEO station would consist of about 135 people, with an individual stay time of about 3 months.

In the 1978-80 timeframe, capital cost estimates for the SPS concepts ranged from $1,400 per kilowatt to $7,000 per kilowatt, with most of the variance due to cost of the photovoltaic cells and construction time. A capital cost of $2,000 per kilowatt, along with other operating assumptions, resulted in estimates that electricity on the ground would cost 5.5 cents per kilowatt hour, which at the time was considered very competitive with alternative energy sources. The DOE/NASA estimates indicated that space transportation would represent about 25 to 30 percent of the total costs, and that 80 percent of transportation costs would be attributable to Earth-to-LEO operations with a heavy-lift launch vehicle.

From a technology viewpoint, the SPS does not require a return to the Moon, but it would benefit economically from the establishment of a lunar base and the development of processing technologies for lunar materials. Only about <u>one-twentieth</u> the energy is needed to deliver a payload from the surface of the Moon to GEO as is required to deliver the same payload from Earth. Because of the potential cost savings associated with this difference, the large number of heavy-lift launches required, and possible negative environmental effects, it has been suggested that SPS construction use lunar, rather than terrestrial, materials.

From the Apollo Program, we learned that random soil samples from the six lunar sites visited contain an average of 30 percent metals by weight (including iron, aluminum, magnesium and titanium), as well as 20 percent silicon and 40 percent oxygen. Some studies have claimed that if 95 percent of the mass of an SPS were obtained from the Moon, the potential savings could approach 30 percent of the total cost.

Mining lunar materials to produce raw stock, fabricating finished products on the Moon, and then transporting all of that to GEO for use in a highly automated construction process, obviously would be complicated and costly, perhaps more costly initially than processing and launching from Earth. Such lunar-based manufacturing techniques would, however, have significant synergism with other activities we already know will have to be performed on the Moon as the exploration program proceeds.

In this sense, SEI opens up a new realm of implementing solar power systems. As can be seen from previous discussions, the thought process in the late 1970's centered on transportation modes in low Earth and geosynchronous Earth orbits. This required a number of launches and greatly expanded human activity in LEO. With a lunar base in the offing, however, extraction of resources from the lunar surface to GEO would relieve much of this burden, as Dr. Peter Glaser of the Arthur D. Little Company has defined in great detail in several papers.[1]

The Lunar-Based Solar Power System

The second method of large-scale solar power generation, based on the surface of the Moon, offers additional advantages, such as eliminating one leg of the transportation scheme and minimizing construction in free space. In a recent study by Dr. David Criswell of the University of Houston[2] and a NASA Case Study[3], this approach has been clearly described and builds on Glaser's earlier work.

The basic concept uses solar energy collected on the lunar surface and beamed as microwaves to antenna arrays on Earth. Linkage to terrestrial power grids, as with the GEO SPS, would be fairly straightforward. Photovoltaic collection and microwave transmission on the Moon produces focused beams received by rectifying antennas on Earth, still in the near field. Matched opposite collection and transmission arrays on the Moon, as seen from Earth, the system would provide for the lunar day-night cycle. Orbiting mirror systems would relay microwave transmissions to Earth's far side as viewed from the Moon. Additional sunlight could be reflected to collectors from light mirrors orbiting the Moon. This concept, developed as a mature system, could channel many gigawatts of energy, using proven basic technology, with passive and low mass equipment requirements.

Early calculations by Criswell for a lunar power system indicate long-term economics to be exceedingly robust in comparison to present energy costs. After factoring in today's environmental concerns and values, the worth of the concept grows. The concept shares many of the benefits of terrestrial solar power but has unique advantages. For example, the intensity of sunlight is greater on the Moon, no clouds interfere, construction can be lightweight in low gravity and the absence of weather conditions, and issues of energy storage during darkness can be avoided. Absolute efficiency will probably not be so significant for solar photovoltaic conversion on the Moon as will be reliability and construction simplicity. And any shortfalls in efficiency can be countered by adding new collection areas. Most impressive, finally, is one last great advantage of this system, and that is a useful power level of more than 100,000 gigawatts.

The Promise of Helium-3

The third method of utilizing the lunar base for energy resources has been documented in an outstanding manner by Dr. Gerald L. Kulcinski and H. H. Schmitt of the University of Wisconsin.[4] Helium-3 is a form of the element helium that is extremely rare on Earth. It has been deposited in the lunar soil by the solar wind for billions of years, however, and samples returned by the Apollo and Soviet Luna missions have verified its abundance there.

Kulcinski has shown that one ton of helium-3 combined with deuterium in a fusion reactor would supply the electrical needs of a city of 10 million for a year. This extremely high power density means that 28 tons of helium-3 (approximately the payload of a Space Shuttle) could have supplied the entire energy demand of the United States in 1987. Even allowing for a selling price of $1 billion a ton, the cost of this alternative fuel is equivalent to oil at $7 per barrel. A helium-3/deuterium fusion reaction would provide a nuclear fuel cycle which contains no radioactive isotopes in contrast to other reactions. The energy released is in a form that could be converted directly to electricity with effectiveness of at least 70 percent. Today's electric power plants fueled by coal, nuclear fission, or other energy sources have effectiveness of only 30 to 40 percent.

The process, which appears theoretically very promising, would involve completely and inherently safe reactor operations. The radioactivity of the reactor is so low that the facility can be disassembled at the end of its life and disposed of as low-level waste, similar to radioactive medical waste. Deep geologic waste repositors would not be needed since this reaction releases as little as 1 percent of its energy in the form of neutrons.

Such a breakthrough energy source obviously has tremendous benefits. It would provide energy to the world through the use of economical and inherently safe fusion reactors. It would mean a new generation of efficient spacecraft to transport humans and cargo throughout the solar system. It would solve many of the energy problems endemic to bases on the Moon and Mars, and would make possible larger settlements on the Moon. And it would greatly reduce the threat of an impending global environmental catastrophe.

The byproducts of mining helium-3 are abundant and in quantities which could foster other growth industries. The process of mining one ton of helium-3 would produce 500 tons of nitrogen, 1,600 tons of methane, 3,100 tons of helium, 3,300 tons of water, 3,600 tons of carbon-oxygen components, and 6,100 tons of hydrogen.

There is no question that the scale is huge and the work required to set up such a lunar infrastructure would be immense. For example, we would need to be able to move approximately 200 million tons of regolith for every ton of helium-3, and the technological advances necessary to achieve fusion reactions are challenging, yet probable.

And as discussed earlier, the Space Exploration Initiative involves a fundamental shift in thinking, 30 years into the Space Age. It is more an approach than simply a program. It means creation of a space infrastructure of space-based operations with a variety of vehicles active at any given time. It implies the creation of a much larger space-based economic sector, not limited just to teflon and communications satellites. This larger economy would expand to include in situ lunar resource development as its centerpiece, not just because such development is likely (and very likely profitable), but also because developing the resources is pivotal to establishing permanent laboratories and other facilities. The scientific and industrial efforts will be married from the start.

As we consider the overall approach implied by SEI, we should bear in mind the societal effects of new technologies and expanded capabilities. The exploration

program will greatly increase our scientific knowledge of the universe, while helping to promote international partnership and the education of our young people. Many of the features of SEI, including the Mission to Planet Earth, could help us solve some of the troubling problems our planet faces.

One of the most far-reaching benefits from the program could come from coupling lunar resource development with a systematic approach to the problem of Earth's finite energy resources. Just as it took the United States two decades to digest the knowledge brought back by Lewis and Clark and then to expand on a systematic program of western expansion, so it has taken two decades to digest the full impact of what Apollo told us about the Moon.

In drawing these strands together, I have capitalized on the work of Peter Glaser, Dave Criswell, Mike Duke, Clarke Covington, Gerald Kulcinski, and many others. What they have shown is that these approaches, in and of themselves, provide compelling reasons to mount the Space Exploration Initiative.

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I_2 SPS interest and studies in USSR

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Abstract

The USSR research of solar energy conversion systems as for the on-board space energy systems of space vehicles and solar space electrical power stations is considered in the report.

The characteristics of modern solar batteries as well as solar energy plants with the dynamic transformation based on Brayton cycle and the ways of their development have been analysed.

The USSR research digest on generation of superhigh frequency radiation in the orbit, its transmission and transformation on the Earth is given.

Résumé

Cette communication présente l'état des recherches en URSS sur la génération d'énergie électrique à partir d'énergie solaire pour les stations spatiales et les perspectives pour les centrales solaires spatiales. On examine en particulier les caractéristiques les plus récentes des panneaux photovoltaïques et des systèmes thermodynamiques fonctionnant suivant le cycle de Brayton ainsi que les perspectives de développement de ces systèmes. Cette communication présente également un résumé des travaux effectués en URSS sur les problèmes d'émission, de transmission et de réception d'énergie électrique hyperfréquence posés par les centrales solaires spatiales. Après un rappel historique des études SPS en URSS des propositions sont faites pour l'avenir, en particulier la suggestion d'une approche internationale.

Intensive exploration of space started by launching of the first automatic and manned spasecraft in the USSR and the USA laid the foundation for the developing the new branch of power engineering - space power engineering.

By the end of the 20th century the development of power engineering on the Earth has come across the number of problems the main of which are its ecological aspect connected with the pollution of environment. It is caused by growth of pollution and consumption of artificial produced energy which by present has reached on average 2.3 kW per person.

Nowadays nuclear power stations, hydroelectric stations and heat power plants are used for energy supply but mining, transportation and burial of their waste cause ecological pollution of biosphere. Moreover with exiting structure of power generating fuel complex ecological damage from disturbing environment will increase. That is why search of new techniques in power engineering assumes ever great significance.

The idea of our compatriot K. Tsiolkovsky put forward as early as 1903 may be considered the most important among them. It consisted in utilization of solar energy/1/.

Space power engineering in the USSR is being developed in four directions:

- power supply for space vehicles and station;
- power supply for power intensive space programmes (development of space manufucturing, interorbital flight with the help of elecrtric rocket engines, for example, transfer from low-altitude orbit to geostationary one, flight to Mars, etc);
- power for utilization of luminuous and thermal energy on the Earth (for example illumination of the arctic region of the USSR during polar nights, lighting of solar power station, etc);
- space power stations.

Besides intensive work has been carried out lately to realize. The project of producing electrical energy in space and its transfer to the Earth which was proposed by P. Glaser in 1968 /2/.

Scientific progress has been thus developing that Tsiolkovsky's ideas were used to meet technical and engineering requirements of numerous space vehicles and stations launched into space during 34 years since the launch of the first artificial satellite of the Earth.

PRINCIPAL REQUIREMENTS TO SPACE POWER SYSTEMS

[----------------------------------]

Taking into account complication of space task, financial restriction, search of ways for using achievement of astronautics in other branches it's inevitable to develop industrial approach in working out and maintaining space power engineering. Varying energy consumption shedule in the conditions of limited power along with rather stringent requirements to voltage stability in the circuit drastically influence power system structure.

For all this power consumption level, difference between minimum and maximum power, parameters stability of

energy source can determine the choice of power system type. The choice of spaceborne voltage quantity must also be dependent upon power level and with its increasing deviation from present standards is unavoidable.

The principal requirement for space vehicle power system is to maintain present varying load schedule adhering to specified tolerances on voltage quantity variation, required reliability level of functioning and keeping to the requirements on mass characteristics and radiation safety condition. Optimization of power mass characteristics of the system must be done taking account space vehicle characteristics as a whole.

Groups of scientists in our country worked out the requirements to the power level and resources of space power systems and also recommendation concerning their types for the period to year 2015. The results are presented in the table 1.

Table 1.
The requirements to the space power systems.

The task in space	Electric power, kW		Resources, Years		Type of power system	
	2000	2015	2000	2015	2000	2015
Communication, investigation of resources, ecology, chart-making, navigation, science	up to 25	up to 50	5...10	10...15	SPS-Ph	SPS-P
Material manufacturing in the orbit	up to 100	up to 1000	5...10	10...15	SPS-Ph SPS-Th	SPS-Th NPS
Removal of toxic waste from the Earth into space	up to 100	up to 500	3...5	5...10	SPS-Ph SPS-Th	SPS-Th NPS
Manned orbital station (life support system)	80...100	500	10	10...15	SPS-Ph	SPS-Th
Interorbital tugs with ERE	20...25	40...50	1	1	SPS-Ph SPS-Th	SPS-Ph
Manned expedition to Mars						
-PEC with reduced thrust(ERE) up to 150	-	up to 15000	-	3	-	NPS
-PEC with full thrust(NRE) up to 15000	-	up to 150	-	2	-	NPES

Notations adopted in the table 1

SPS-Ph - solar power system with solar cells;
SPS-Th - solar power dynamic system ;
NPS - nuclear power system;
NPES - nuclear power engine system;
PEC - power engine complex;
ERE - electric rocket engine;
NRE - nuclear rocket engine.

RATIONAL FIELDS OF USING POWER SYSTEMS

Each type of power system has its rational field of utilization.

These fields are presented in Fig.1 on the coordinates "output electric power" - "operation time".

Notations adopted in the Figure 1 :

CPS - power systems with the open cycle on chemical fuel;
CSC - chemical sources of current (accumulators);
ECG - electric-chemical generators;
NPS - nuclear power systems;
SPS - solar power systems;
RIPS - radioactive isotope power systems.

This figure shows that the regions of electric supply systems with the closed heat cycles with the solar , nuclear and radioisotopic sources of energy and with phototransformers are situated in the region of existance time from a decade and more.

The solar energy plants, possessing clear ecological attraction have some shortcomings nowadays:

-accumulators (chemical or heat) for supplying consumers on the eclipse parts of trajectory are required;

-large panel areas of photovoltaic transformers(PhVT) and concentrators are required;

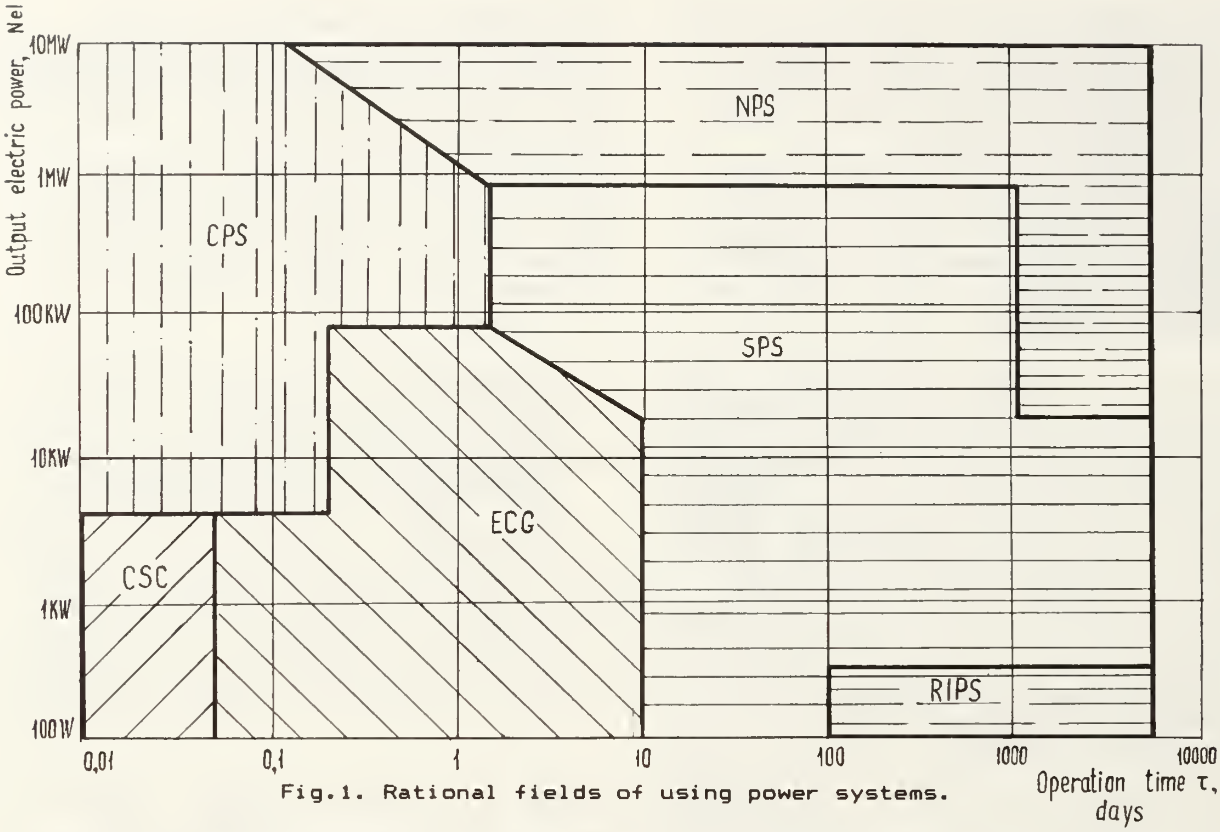

Fig.1. Rational fields of using power systems.

-high accuracy of tracking the Sun (1 ..4 degrees) is necessary;
-degradation of PhVT characteristics, which can essentially increase in the radiation zone of the Earth;
-large surface of solar panels can cause higher aerodynamic resistance and low dynamic chartacteristics (especially for big power plants);

The resource of solar plants with PhVT (photovoltaic transformers) will be defined by the rate of their degradation and can make up some years; the level of power must not exceed 100 kW. But higher efficiency and corresponding decrease of the concentrator surface of the solar energy plants with the machine cycle (SEP-Th) permit to raise the power level to 0.3-1.0 MW.

A considerable danger in accident is an essential deficiency of nuclear power plants. To increase the security it is expediently to use the nuclear power plants to solve such problems which can't be solved in any other way (for example, expedition to the Mars) or in an alternative variant require considerable financial spending. At present the reasonable electric power, with which nuclear power plants will be expedient make up about 25 kW in the range not less then 5 years. The high power level , as concerning the consumptions of Mars expedition can make up 15 MW. The high power plants may have a module construction.

PERSPECTIVES OF THE DEVELOPMENT OF ON-BOARD SPACE ENERGETICS

Examining the diagram of increasing the maximum power being used in the energy plants, which you can see in Figure 2. It's necessary to point out tendency of rectilinear increase of power in semilogarithmic scale along the time coordinate.
Both last types are not alternative supplying different space problems.
It is natural that as the range of the using powers expands the types of required power plants are expanded. Radioisotopic thermoelectric and thermoemissional, electrochemical based on the heat elements power plants have been added to storage batteries and solar cells. Nuclear energy high power plants and solar plants with the dynamic cycle at middle power level are considered in perspective.

SOLAR ENERGY PLANTS

Solar energy plants with planar batteries keep their prevailing position for the power level of 15... 20 kW. With electric power more than 15 kW it is more advantageous to use higher voltage than 27 V and alternating current. That's why we begin to consider the solar plants with the machine transformers, for example the plants based on the Brayton cycle, from this power level. This transformation has a number of

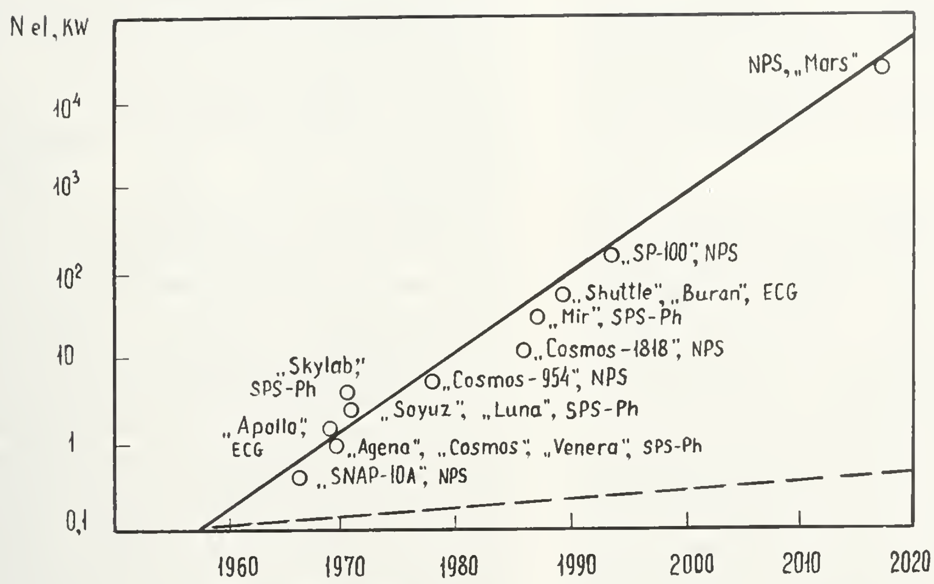

Figure 2. The development of power plants according to their power level.

advantages: the efficiency of transformation really achieved 20...30 percents, there is an ability to receive an electric energy and heat simultaneously. The plant may be unified by using either solar or nuclear source of energy.

SOLAR ENERGY PLANTS WITH PHOTOTRANSFORMERS (SEP - Ph)

Space vehicle power systems were traditionally based on planar batteries as a primary energy source and on balancing batteries as a secondary source for on-board apparatus feeding in eclipse parts of orbits and at the "extreme" loading.

I'll demonstrate the development of the power supply systems of space vehicles on the example of the world known "Cosmos" satellites. "Cosmos" satellites are the main means for the vast space research not only by our country but also by many other countries of the world.

The first "Cosmos" satellite was launched on March,16,1962. The energy source of this and the following satellites was the silver-zinc storage battery. The necessary power didn't exceed some watts, existence time-from 10*24 hours to 50*24 hours.

Starting with the artificial Earth satellite"Cosmos" launched on June 30, 1962, the power supply systems use the silicon solar batteries. Their power was up to about 30 W, life time - 1440 and more hours.

The beginning of exploitation of a number of automatic unified orbital stations oriented to the Earth(AUOS-E) was another step in the development of power systems made in 1976. The power system of these satellites comprises a silicon solar battery non-oriented to the Sun (autonomous of satellite) with a total area of 12 m*m, two air-tight nickel-cadmium storage batteries with a total capacity of 66 A*hours,control devices.

The power of energy system raised up 150...200 W, the active life time - up to 180*24 hours. The real service life greatly exceeded the designed one up to 5 years on the satellite "Oreol-3".

In 1979 the program "Ocean" began and several satellites were launched. The power system of these satellites comprises the •one-axis Sun-oriented solar battery with an area of about 7 m*m, its power level is 180...400 W.

The lunching of the automatic unified orbital station - solar modification (AMOS-SM) is planned for 1992. The minimum power level of the designed power system is 850 W. The system has a silicon solar battery oriented to the Sun with an accuracy of 1 degree,its area equals to 18 m*m. The active life of AUOS-SM is a year.

The launching of the satellite "Ocean - 0" is also planned for 1992. This satellite will comprise the one-axis Sun-oriented silicon solar battery (SB) with an area of 32 m*m. The power level of the system will be about 1500 W, an active life of the satellite "Ocean - 0" - a year.

The characteristics of the solar batteries installed in the satellites have been constantly improved and the present real characteristics are as follows:

-specific power is about 125 W/sq.m at the beginning of the exploitation, performance temperature +60 degrees C;
-specific weight dependent on the requirements of radiation resistance is 2,8...3,3kg/sq.m (phototransformers with the elements of commutation and cover glasses without the weight of the frame.

Our achievements are:
-we were first to use the photoelectric battery in the satellite "Oreol-3" of the "Arcad" project the design of which allowed to diminish the magnetic and electric fields created by the SB (the so called electromagnetic pure SB);
-the achieved operating time of solar cells is over 5 years in the circular orbits as high as 500 km;
-the usage of the carbonplastic frame as the bearing construction allowed to improve specific weight characteristics of the frame from 3,6...3,2 kg/sq.m up to 2,4 kg/sq.m (i.e. in 1,5 times);
-we designed the reliable locking mechanism of the SB,folding mechanisms for putting SB into the operating position using the material with a "memory effect".

At the AUOS-SM we shall carry on research of the photoelectric plant with the solar energy concentrators.We suppose to solve the problem of raising life time resource and the efficiency of energy transformation and to reduce the costs of power systems.

The installation comprises four experimental panels with PhVT made of Si and GaAs, coefficients of concentration are 3, 4, 30, 60.

I would like to tell you about "Oreol" stellite more carefully. One of the most important experiment of the Soviet-French space project"Arkad" was realized with the help of this satellite having been launched on the 21 of September 1981 into the orbit with the following parameters: the hight of the apogee- 2012km; the hight of the perigee - 408km; inclination - 82,5 degrees; the period of rotation - 109,5 min.

The aim of the project was to carry out the wide complex research of physical processes in magnetosphere and in the polar high atmosphere - ionosphere, to study magnetospheric - ionospheric ties.

An electromagnetic purity of a satellite plays an extremely important part in relatively precise measurements (with an accuracy to 10 nTl).

Special attention was paid to the providing of the solar batteries and the whole system of electric supply with the electromagnetic purity.

Prognosis analysis of space vehicles development shows the increasing of demands to the means of their power supply which is connected with broadening of the tasks to be solved, increasing of the quality of information obtained,the degree of its on-board processing,operativeness of transmission and summary informativity.

Power requirements of the USSR space programs are 10...100kW daily average in prospect.

Solar Power Systems (SPS) with above mentioned power level requires special approach to their development connected with the following considerations:
-limitation in weight and volume occupied by power installation under the rocket booster fairings;
-financial limitations existing for space programs;
-limitation in possibility to achieve in acceptable period of time high specific characteristics of the PhVT used in planar solar cells.

On the basis of the elaborations made under the guidance of M.B.Kagan it is supposed to increase by 2000 both the specific characteristics of the phototransformers and planar solar batteries up to the values of 140...170 W/sq.m for silicon PhVT and 190...220 W/sq.m for gallium arsenide PhVT.

A great contribution to the solution of the problem of PhVT improvement has been made by the scientists of Leningrad Physics and Technology Institute of the USSR Academy of Sciences under the guidance of academician Zh.I.Alferov and by the Scientific Production Amalgamation under the guidance of A.M.Rzhevsky.

PhVT improvement in the USSR is being carried out in the following main directions:
-directed improvement of semiconductor structure specifications by its optimum alloying and creation of built-in electric fields;
-transition from homogeneous to heterogeneous and varizone semiconductor structures;
-creation of cascade PhVT made of specially matched at the width of the "forbidden" band of semiconductors allowing in every cascade to transform the emission passed through the previous cascade and others.

We consider the usage of concentrating systems to be the further step to improvement of solar batteries. Their application will allow both to reduce the SB costs due to the lessening of the square occupied by PhVT and to increase its resistance to cosmic radiation owing to screen effect of concentrators, to diminish the rate of PhVT degradation by temperature defects annealing. However the SB with concentrators have an essential shortcoming - the necessity of accuracy in orientation to the Sun.

The degree of solar radiation concentration for silicon PhVT reach several dozens, and several hundreds for PhVT made of gallium arsenide.

SOLAR POWER SYSTEMS WITH MACHINE TRANSFORMATION

In the machine transformers of space

power satellites known nowadays Brayton, Rankine and Stirling thermodynamic cycles are used.

A number of technological difficulties which we come across at present made the scientists in our country to develop power systems operating by Brayton and Stirling cycles.

The development of turbo-machine way of transformation is stimulated by a number of its virtues, the main of which to our mind are:

-higher efficiency in comparison with other solar energy transformers;

-possibility of easy transition to high values of on-board voltage when constructing high power systems;

-possibility to provide both voltaic and heat needs;

-presence of waste separate constructive elements of such installations in other branches of industry(compressors,turbines,bearings etc.);

-possibility of power control according to a given power consumption schedule.

Due to specific requirements to space power, having appeared recently, turbine machine transformers gained one more advantage:

-relative invulnerability to corpuscular particles flow , to electromagnetic radiation and other outer space factors.

A mixture of noble gases(He+Xe) is more frequently used as an operating body in such plants. This operating body is heated in heat receiver. Heat receiver can be either combined or not with heat accumulator.

The presence of heat accumulator(HA) is explained by the necessity of power supply of the consumers on the eclipse parts of the space vehicle trajectory.

The greater square of the solar power concentrator surface can allow to create a developed heat reject surface at low financial and weight costs. It gives an opportunity to decrease the low cycle temperature and consequently to increase the thermodynamic efficiency of the plant.

A number of questions has to be solved when such power systems are being worked out.

In the field of technology:

-creation of new materials for concentrator covering, light absorbing materials for heat receiver and their approbation in outer space condititios

-compatibility of construction materials with phase change materials;

-designing of reliable rotor bearing that provides a given life time .

In heat transfer:

- distribution of radiant heat flux along the real receiver construction, that is necessary to avoid construction elements burnout;

-heat transfer of semitransparent phase change material;

-performance both of separate units and the whole power system in non-stationary operating conditions etc.

There's a number of difficulties connected with the peculiarities of such type of power systems. They are:

- the nessecity of the accurate orientation to the Sun (1...1.5degree);
- the presence of the gyroscopic moment.

We think that the creation of such power system with the power up to 1 MW within the framework of SPS does not meet the principal difficulties and a number of problems will be taking away, such as :

- high efficiency of the turbine and compressor will be provided;
- provision of the high degree of recuperation.

The precence of gyroscopic moment in this case may become a stabilizing factor for the SPS.

In the USSR at present there are 2 design of the dynamic power system with the Brayton cycle of the operation with electric power of 3.5 and 10 kW respectively. The energy system with the power of 3.5 kW is being developed by the " Foton" experinental laboratory at the Dniepropetrovsk University.

The results of the preliminary development of this power system will be presented in my report at the section A4 . The energy system with the power of 10 kW is being developed by the working group headed by Semenov V.F.

The working group headed by Samsonov V.L. at Moscow created the closed contour of power conversion unit , which has the operation time of 1000 hours.

The efficiency of the turbine and compressor equals to 0.8 and 0.87 respectively. "Foton" has created the real designs of concentrator and the heat absorber. They are being tested at present. Following characteristics have been achieved:

- number of cycles - 250;
- maximum temperature - 1150 K;
- reflection coefficient - 0.92.

Selected performance for the 10 kW power system at present time are follows:

-turbine and compressor efficiency are 0.9 and 0.85 respectively;

-rotation frequency - 24000 cycles per minute;

-resource of experimental work - 100 hours;

-the degree of recuperation -0.9.

The working body pressure at inlet of the turbine was 4 atm.,temperature-1100K.

The specific weight of such type system reached in our country is up to 40-45 kg/kW.

During the development of both units and subsystems a number of problems connected with the problem af start, regulating, stop etc. arose.

One of the advantages of such power system is the possibility of compatibility of concentrating and

receiving subsystems with the other transformers. The original thermoelectrochemical converter for solar power system with the efficiency about to that of Carnot cycle has been developed at Moscow Aviation Institute under the guidance of L.A.Kvasnikov.

We hope that such a type of power systems will find its place in the SPS program.

SPACE POWER STATIONS GENERAL IDEA OF THE PROBLEM

One of the new technologies in energetic is the supply of the Earth with energy from space where its resources are practically unlimited. According to prognoses, by the 2030...2040th there will be a global abatement in fuels output because of their limit. The structure of energetics according to scientists A.S.Koroteev and V.F.Semyonov will be as given in the Table 2 /3/.

Table 2.

The Structure of the Earth's Energetics by the 2030...2040th.

Types of energy consumption on the Earth	The structure in 1991 given in % (percentage)	The structure by the 2030...2040th: The type of energy source	Percentag
1. Lighting	5	ground	4
		space	1
2. Electricity excluding the lighting	20	ground	10
		space	10
3. High potential heat for industry	20	ground	10
		space	10
4. Fuel for transport	30	ground	30
5. Supply of district heating systems	25	ground	20
		space	5
Total	100	ground	74

As it is seen from this table the part of energy taken from space will increase by the 2030...2040th up to 26%.

THE USE OF SPACE ENERGY

The use of achievements in field of cosmonautics will allow to realize the following main trends in space energetics:

-the lighting of polar regions of the Earth with the help of orbital reflectors on the basis of thin film mirrors;

-the growth of biomass production on the Earth by means of increase of the light day length;

-the increase of energy output of ground solar electric power stations due to additional illumination;

-the transmission of energy from regions reach in energy resources to the regions which have none of them with the help of superhigh frequency radiation and passive orbital radioreflectors;

-supply of some parts of the Earth with the energy from orbital solar space electric power stations (SPS) which transform solar energy in microwave radiation and send it to the Earth;

-heat supply of power technological ground complexes with the help of laser radiation generated in the orbit directly from solar radiation.

In future, as the number and the part of SPS in power supply increase, it will probably be economically profitable to create them from materials obtained from lunar ground and place them on the Moon.

WAYS OF SOLVING THE PROBLEM

The creation of "Power Supply from Space System" should be done step by step.

The solution of this problem will be greatly dependent on the development of highly effective space vehicles. For example, this problem can be solved by the presence of powerful space energy units on low Earth orbits, these units being able to transfer the energy to the Earth remotely. This will create a new type of launchers which can use outer sources of energy.

The deployment of space energy units infrastructure in orbits and industrial production of some materials in space and their maintenance will demand the presence of specialists at prolonged orbital stations with comfortable life conditions. In this connection the role of space station "Mir" is of great importance.

The work of life-sustaining system in "Mir" will open the possibility of designing the economical orbital stations and also planetary bases for prolonged operation.

In order to solve the problem of creation "Power Supply from Space System" successfully, it is necessary to develop the following:

-launchers;
-energy suppliers;
-life-sustaining systems;
-means of space production.

Let us examine in detail the energy supplying systems, the work upon which will pass from the scientific research stage to the experimental-designing one in the nearest future.

These systems will include:

-light concentrators of solar energy and orbital thin film optical reflectors;

-orbital radioreflectors of large diameters;

-effective combined phototransforming and microwave emitting system;

-light phased antenna grids and receiving aerials;

-closed gas turbo-engine contours with the efficiency up to 50%;

-highly efficient lasers with the efficiency from 20 to 30%;

-systems of heat reject into cosmic space based on drop refrigerators-emitters;

-energy accumulators with specific capacity up to 500 kJ/kg and low specific mass (about 1kg/kW electric);

-electrotechnical devices using the effect of superconductivity.

THE ACHIEVEMENTS IN SOLVING THE PROBLEMS CONNECTED WITH THE CREATION OF SOLAR SPACE ELECTRIC POWER STATIONS (SPS)

The idea of creation of SPS was proposed by the soviet engineer N.A.Varvarov in his article /4/ as early as 1960. Therefore the investigations made by Peter Glaser were of great interest in the Soviet Union. It is necessary to mention that the first volume of "Heliotechnika" which was published in 1971 included the translation of Dr Glaser's paper.

Since 1977 the leading research centres of the USSR have been involved into the development of different aspects of SPS creation problem/5/. These studies were continued in our country even in the early 80-ies when the negative solution on the DOE-NASA project caused the recession of the interest to the problem abroad.

For the last 5 years there is a revival of interest to SPS, which is stimulated by a stored theoretical material and new possibilities in cosmonautics connected with the appearance of the powerful launcher "Energy" (to realize the demonstration SPS project only 3 "Energy" launches are required).

Practically all the questions arisen in the process of SPS development were reflected in the works of soviet scientists: methods of transformation of solar energy into the electric form; installation of the power satellite into the geosynchronous orbit; energy transmission to the Earth by microwave radiation.

It is necessary to draw attention to the investigation of ecological aspects of using superhigh frequency in transmission of energy/6/.

An interesting solution of the problem of launching of heavy loads to orbits with the use of electromagnetic gun and the effect of anomalous pressure in ionospheric plasma was proposed by B.A.Osadin. There are original projects of SPS elements transfer from low orbit to geosynchronous one with the help of electric rocket engines with outer feeding (the transmission of microwave energy "Earth - Space")/7/.

The scientist worked hard upon the questions connected with the formation of microwave beam at Space station, its passing through the atmosphere and its transformation into direct current energy for the ground consumption.

A group of scientists from Leningrad under the guidance of Dr V.A.Grilikhes developed the idea of direct transformation of solar energy into microwave emission by coupling of two main subsystems of SPS: solar cells and phased antenna grids - into one solar active phased antenna grid (SAPAG) which consists of separate active semiconductor modules /8/

This group for the first time succeeded in realization and testing of SAPAG where principally new photoelectric generators of microwave radiation were functioning. They include non-linear semiconductor structures in which autooscillations are aroused because of inner feed-back in case of negative differential conductivity.

Dr V.V.Rybakov with collaborators (Moscow Aviation Institute) proposed a new method of generation of microwave radiation with the help of plasma ionic engine.

The space power group headed by Dr V.A.Vanke at Physics Department of Moscow State University has developed the methods of synthesis of highly effective antennae with a low sidelobe level /9/. It has been proved that strict standard of radiation security adopted in the USSR (<10mcW/sq.cm) can be observed and so do the demands of electromagnetic compatibility (<0,27 mcW/sq.cm) over the limits of the receiving antenna. One of the latest investigations of this group is the unique antenna with radially polarized emission which doubles the transmitted power for the fixed values of maximum energy fluxes at inlet and outlet of energy transmission channel.

For the first time the idea of optimum density of rectenna converters on the square of receiving antenna was analysed at Moscow State University. It turned out that 80...100 units per 1 m*m will provide the maximum effectiveness of transformation of microwave energy into direct current. A powerful cyclotron transformer of superhigh frequency emission into direct current has been developed. It produces dozens of kilovolts at the outlet with power up to 50 kW. This greatly increases the reliability of the ground system.

The results of our investigations

prove that: it is possible to realize the idea of solar space power stations, some elements of space power systems have already been developed and the realization of the SPS demonstration project is delayed only because of lack of financing.

It is necessary for the governments to use more balanced approach to the long-term power programs. Now large resources are spent to solve the problem of controlled nuclear fusion which is far from being realized even as a laboratory unit.

There is one more important conclusion which can be made from the research work: the problem of SPS creation is very complicated and requires the solution of the great variety of different problems such as biological, ecological and social.

To my mind, the Universities are to become the centres of their solving. Soviet Universities come out in favor of a proposal of Universities cooperation in the problems of Solar Space Power Stations on a world scale.

We call upon for international cooperation in the field of creation of engineering orbital complexes. To our mind the creation of the industrial complex on the near-Earth orbit would permit to solve the following problems efficiently from the economic point of view:

-production of biopreparations in the conditions of weightlessness;

-production of especially pure semiconductor materials,manufacturing of which is impossible in the conditions of Earth;

-systematic research of the Earth surfaces in the interests of ecology, geography,meteorology,navigation etc.

The service of the engineering complex may be provided either with the long stay crew in the orbit or with the watch method. Artificial gravity and other "earth conditions " may be set up in the orbital complex.

The creation of orbital settlement with the help of international cooperation is quite a real problem.

In our symposium I propose to consider the question of establishing the international association for the development and realization of the joint project of multifunctional research-engineering orbital complex which ought to become the first on the road of wide range developing of space energetics.

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I_3 New Earth 21 Action Program

Jun OKUMURA - MITI, Tokyo, Japan

The Earth's atmosphere, land and ocean are spoiled with exhausts, wastes and pollutants that are all man-made. Preservation of the global environment has become a major world concern. Especially, discharge of carbon dioxide has continued to increase since the last industrial revolution. The enormous growth in the human population combined with social pressure to improve the standard of living for peoples of all nations through economic development, has accelerated the production of greenhouse gases. The Ministry of International Trade Industry, Japanese Government, warned that even if advanced countries maintain carbon dioxide emissions at present levels, the world's total carbon dioxide discharge would be more than double by 2050, and triple by 2100. MITI began to consider a concrete program, the so-called "New Earth 21 Action Program" aimed at lowering levels of carbon dioxide and other greenhouse gases over a period of 100 years. Japan proposed the action program at the Houston economic summit and the idea was included in the summit declaration.

Contents of the action programs are shown below :

1) Adopt energy-saving policy in all areas related to industry and transportation, and reduce the scientific uncertainty through measures such as a global monitoring system by satellite,

2) Utilize renewable energy and nuclear energy,

3) Develop innovative environment-friendly technology,

4) Expand forests as carbon dioxide absorbers by afforestation and preservation,

5) Develop innovative power generation technology like solar power satellite nuclear fusion.

I_4 GSEK - Global Solar Energy Concept

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The ultimate goal of GSEK, a global solar energy concept created by MBB, is the safe and inexhaustible supply of power on an ecological and economical, large-scale industrial basis. For assessment of chances, risks, challenges, benefits and technological gaps three equivalent system concepts are considered in parallel. The measure for two space-based competitors is a bare terrestrial systems concept.

The present favourite is a mixed systems concept. Combining power generation on the ground and in space by means of laser illumination of solar power plants on Earth, it multiples the power output of the latter, eliminates the need for dedicated expensive rectennas and for large day/night energy storage. Without the risk of wasting time and money, the ultimate decision of no return is postponed to a future date when it can be drawn on the sound basis of an adequate technology program running in parallel with the erection of dedicated terrestrial receiving plants.

Conceptual design and analysis of an orbital power station is a necessary but insufficient prerequisite for realistic assessment of the potential of power from space. Covering the aspects of ecology, economy, technology and operations, an operability and life cycle analysis of an overall industrial systems scenario is required, which includes the harmonized technical and operational concepts for power stations, in-orbit infrastructure, traffic/transportation, operations, maintenance/repair and final disposal.

Consideration of transportation is inevitable, because it governs economy and ecology of power from space. Harmonization of the concepts for orbital power stations and for transportation significantly reduces classical transportation mass, related cost and atmosphere pollution.

The operability of industrial power generation in orbit affects all sub-scenarios, even optimum design/size of power plants, and calls for international agreements and regulations.

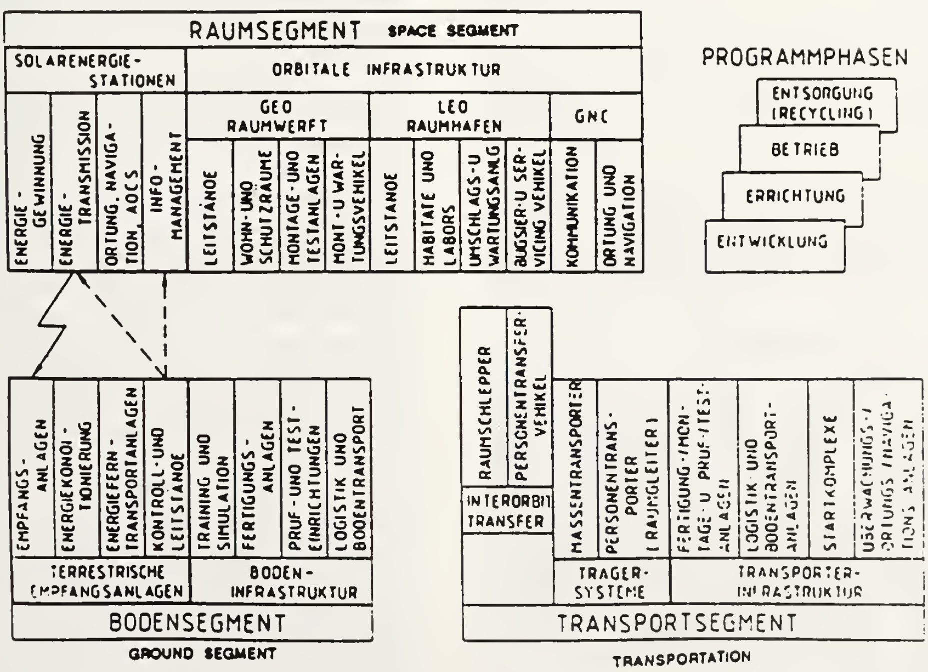
Ground safety and operability favour modular multi-beam transmission. Hundreds of identical laser sub-stations simultaneously beam energy onto a common receiving site. The intensity of the superimposed beams on the receiver is within acceptable limits; core intensity of each of the individual laser beams is far below the exposure limit for the unprotected human eye.

Although burdened by the effort of transportation into orbit, power from space turns out to be a serious and safe alternative for the future. If design goals can be met, it promises superiority over terrestrial solar power plants, regarding geo-political vulnerability and safety of supply, economy, ecology and energetic pay-back. In terms of ecology it rules out conventional fossil-fuelled power systems by some orders of magnitude.

A survey of the presently favoured orbital variant of the global solar energy concept

will be given. All the major aspects of industrial generation of power in space mentioned above will be addressed, such as : demand and overall system requirements, long-term strategy, harmonized systems scenario and the logic behind aspects and impacts of operability and mission analysis. A generic design of a space power plant and a corresponding ground receiver will be outlined, including configuration, design features and design goals, major sub-systems, functions, performances, masses, operations and design sensitivity. Finally political, ecological, economical, technological and operational aspects will be treated, and preliminary requirements and conclusions will be drawn.

GSEK - SYSTEMS ARCHITECTURE



I_5 Energy Crisis and SPS for third world future

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Beyond a doubt, this is an age of contradiction : while on the one hand we have an unprecedented explosion of knowledge, more than 6O% of the people on the earth remain illiterate; while we have the potential to grow enough food for everyone, 42% of the people in the developing countries go to bed hungry. Around 0.4 to 1 billion people remain undernourished. While we are about to explore the farthest reaches of the outer universe, and while the unlimited energy sources of the sun remain unused, energy shortages in most of the countries of the world cripple their development efforts.

Mankind is at a crossroads. Never before has such immense potential for development and destruction been at his command as today. If we succeed in using our vast array of knowledge acquired through our understanding of the laws of nature and the technical mastery of the secrets of the universe, we should be able to convert many of mankind's visions into future realities. Knowledge, like problems, knows no boundaries. For the first time scientific knowledge can be applied globally to human problems.

Man's main concerns since the beginning of history have been security and development by mastering the universe (whatever its size and shape, perceived at a specific moment in time), and in institutional arrangements.

Among the many developments during the more than 2 million years of man's life on Earth, the one which has dramatically altered the course of his future was the Industrial Revolution of 300 years ago, with unprecedented control over the physical universe. At each stage of his advancement, man confronted many complex problems some of which were resolved, while others became more intricate, posing a challenge for future struggle. None of these difficulties, however, have deterred efforts to pierce through the mysteries of the problems faced in order to move towards a new stage of research. Internationally a multitude of problems confront mankind today, and the scenario seems rather grim and unpredictable. With 5 billion people in the world, there is still a strangulating population explosion at the rate of 2 % a year which, according to several forecasts, will bring the population to 7 billion by the end of the century. Two-thirds of these people, living in more than 100 countries are as removed from the industralized civilizations of Europe, North America, Russia and Japan as they were for millenia. There is a threat of a cataclysmic nuclear war which can eliminate all forms of life. There is extensive environmental degradation around the world, posing a serious threat to health and even survival. There are widening and shocking inequities between the 35% of the people who have, and the rest who have not, which may

engulf them in a destructive conflict. And last but not least, there is serious and deep concern about the exhaustion of Earth's material resources due to the insatiable and relentless consumption by ever increasing numbers, driving man to the last stage of poverty. These problems are by no means simple, nor can they be solved by one nation or a group of nations, nor do we see their immediate solution. It does not seem likely that man will go back to the tranquil, isolated, confined, non-technological existence of the past. Once known, it cannot be unknown whatever the price man may have to pay. Man's relationship with nature and the universe has been permanently changed.

SPACE AGE AND THE GLOBAL FUTURE

It is in the context of the above state of the world and man's knowledge that we must explore the future of mankind. Evolution continues forever. We do not know whether man's nature is undergoing any fundamental change due to the new environment in which he presently lives. Industrialization, a system of mechanical production with an increasingly large number of products for consumption, and urbanization, an agglomerated settlement with huge numbers of industrialized people, are new dimensions of the future. Once man crosses the boundaries of the Earth, another undefined and important dimension has been added. At this stage we can hardly measure the unexpected impact of space development on man and his future. As the new potential of space becomes possible, man's relationship with man and his universe will require fundamentally different arrangements from the ones he has designed and lived with so far.

At the outset the nations of the world must resolve what their priorities are in order to justify the exploration of space. All new ventures are expensive, and those who have waited indefinitely for the benefits of industrialization cannot wait any longer. The new exploration must accelerate the process by which it can join the mainstream. Hence the need for an immediate cost-benefit analysis of each space exploration.

As the world enters an age of automation, space industrialization is the next stage of development. Space industrialization, as defined, is a production of material, goods, and services through developments in space. Barring space military ventures or other negative impacts on human life or on other life forms, it is hoped that if space developments are to be justified they must benefit mankind, directly or indirectly. Such benefits are to be considered in the light of other possible alternatives for meeting the urgent needs of the vast majority of people. At this juncture in the history of mankind, space cannot be considered in a vacuum or purely for the sake of exploration. Therefore, those who are seriously concerned about space exploration should apply the following criteria:

1. Any such venture should be an international collaboration between industrialized and less industrialized countries through the United Nations or any such international organization, if possible.

2. Space laws should be designed to protect the global interests of people and their environment.

3. A set of specific priorities should be set in order to solve the urgent problems plaguing humanity.

4. While political, social, and economic institutional rearrangements may be necessary, societies must be protected from total destruction.

5. In order to maximize the benefits, different stages of space science and technological developments should be set in terms of financial commitments for specific projects, which will accelerate developments in the third world.

As it is, whether we know it or not, imperceptably and slowly, the world is affected by space development almost every day either through space satellites circling the Earth or travelling in space or through a vast array of research and development projects being carried out to test the various applications in human affairs. These research and development projects are testing the following :

1. Recovery of material resources from outer space, such as the Moon, asteroids, or other planets.

2. Production of new types of materials outside the Earth's environment and gravitational field.

3. The development of new industrial processes not possible on Earth.

SPACE AND TRANSNATIONAL DEVELOPMENT

Since the orbiting of Sputnik 1, space developments, with all their subsequent scientific and technological innovations, have influenced a vast array of fields such as communications, medicine, food production, weather, navigation, education, geological studies, ecology, transportation etc., not to mention astronomy, physics, and planetary sciences. It is not possible to expedite the process of development globally in order to meet the specific desired and desirable needs of people living in different cultures. Already some of the benefits are reaped by a large number of countries, particularly in the field of communications; for example, the "Early Bird" launched in 1965 and other satellites, such as Landsat, provide information for planning and development. These ventures have already proved that with transnational cooperation the economic, technological and resource capabilities of many countries can be increased for their mutual benefit. As can be expected, a great deal of investment in these projects has come from a few industrially advanced countries; yet directly or indirectly, most of the countries of the world have benefited from these initial stages of space application.

While industrialized countries would expect somewhat different benefits of space from developing countries, there exist many common areas of interest. For the next 10 years, such interest can be divided into the following three categories :

Industrialized Countries:
Medicine, Tourism, New Products, Electronic Postal System, Electronics.

LDC's:
Agriculture, Education.

Global :
Communication, Energy, Transportation, Disaster Prevention and Control, Environment, Material Processing Resource Survey, New Material Development.

4. The manufacturing of products in the space environment.

5. The development of technologies and techniques which are difficult to carry out on Earth.

6. The measurement and understanding of the impact of the space environment on man and other life forms.

With all these explorations, it is hoped that mankind will benefit in the long run by extending his knowledge and control far beyond the confinement of the Earth. In a sense, such knowledge can have the impact of liberation which man never could have conceived within the boundaries of limited space on Earth. One question we must ask is : Has man the vision and courage to penetrate the universe in order to liberate these potentials to benefit everyone ?

It is estimated that internationally more than a billion dollars a year is presently spent on space-related activities. The U.S., which has been in the forefront of space technology, has reduced its commitments significantly as of late. Now that it is proven without a doubt that space developments are indispensible for the international communication systems, the potential of this can be fruitfully and effectively applied to most of the developing countries, since many of their problems are rooted in the lack of generation and transmission of information.

At the same time, developments in the areas of transportation of energy and large-scale space constructions ought to be pursued vigorously during this last decade of the millenia in order to bring the fruits of these developments to other pressing areas such as the transport of materials and people, and the development of the solar power satellite as propounded by Dr. Peter Glaser and others. As a natural sequence to this, many not so exotic and even necessary developments are possible. Among them two should be mentioned :

1. The transfer of high-polluting industries or manufacturing systems to space, thereby protecting the environment of the Earth. Eventually this will be necessary in order to provide higher standards of living to all the people of the world. We have estimated that in terms of resources and environment capabilities, only 500 million people can be provided with a standard of living enjoyed by the average person in the United States.

2. Despite great controversy concerning their desirability or even necessity, the space cities, suggested and designed by Dr. Gerard O'Neil and others, will be another sequence of space industrialization during the first quarter of the next century. Beyond that, possibilities of space remain limitless.

As far as developing countries are concerned their principal desire is to build viable economic systems with the help of a type of industrialization, including space

technologies. They must leap-frog into the modern age at a minimum cost without disrupting their social fabric and traditional cultures. Some fundamental changes are inevitable with exposure to the planet's society and education. No society can remain static if it is to survive, least of all in a space age. Once the boundaries of Earth are broken, man and society can never be the same.

In short, space developments can provide benefits in the following priority areas in less-industrialized countries :

1. Disaster Warning and Environment:
As described by the report of the United Nations Regional Seminar on the use of Satellite Technology for Disaster Applications, satellite information on disaster warning can be advantageous applied by developing countries. The satellite remote sensitive imagery is helpful not only for storm and flood warnings, but also for the assessment of flood damage, hydrological and climatological changes including desertification as well as air and water pollution. For example, the photographs from the satellites showed the cyclone formation in the Indian Ocean & Bay of Bengal before it struck the coast of Bangladesh, killing thousands of people, with total damage of over one billion dollars. On average, less industrialized countries suffer a damage of approximately 1.5 billion dollars a year due to such disasters. Today space science can help prepare for better protection from natural disasters.

2. Agriculture:
By participating in the meteorological satellite programs at the cost of only $20,000 to construct a ground station, the LDC's can plan and manage their agriculture more efficiently and beneficially. After all, 90% of people in China and in Africa, 75% of people in India, and 65% of people in South America depend on agriculture for their livelihood and survival. The loss of existing agriculture is estimated at 6.5 million hectares due to erosion itself. Five per cent of the national income in India is contributed by agriculture which depends on the vagaries of the monsoon and climate. Space developments can offer forecasts concerning weather, water tables, and pests. Various calculations concerning agricultural planning in India suggest that better rainfall predictions can help save 1 to 1.5 billion dollars a year in agricultural production. The encroaching desertification in Sahel, which brought one of the worst disasters due to drought between 1968 and 1973, could have been controlled by examination of the data available through remote sensing. Landsat data have been useful in recent years in managing forests in Thailand, agricultural development in Upper Volta, and crop surveys in Brazil. Simple calculations show that with an investment of 5 cents a farmer, the benefit in terms of long range agricultural planning will be in the order of 40 cents in food production, not counting better health, a higher standard of living and other rewards.

3. Education:
Most developing countries have 60-70% of their population illiterate, deprived of even the basic information necessary for their survival and development concerning health, family planning, agriculture, national development and scientific and technological breakthrough. TV educational programs can provide easy information in remote areas of these countries. A community TV set can serve as a means of education to as many as 100 people. The cost of the hardware is hardly twenty rupees a person. In India, a successful satellite TV education program was launched in 1975, and it proved the value of such education in improving the quality of life of the villagers in the exposed areas. It would be a mammoth task to bring education to 560,000 villages in India, but the space education system can expedite the process at a minimum cost by eliminating the cost of an enormous number of classrooms and teachers.

4. Communication :
For education, disaster warnings or personal emergencies, most of the less industrialized countries suffer from the lack of communication facilities. Whereas there is one telephone for every 2 people in the U.S., there is only one telephone for every 50 people in developing countries, most of which are concentrated in urban areas. How can these countries expect national integration and national development without the basic means of communication available to the people, especially in remote areas ? The knowledge explosion apart, most of the villages of the world can be inter-connected by telephone or any other communication system through space technology within 10 years at the reasonable cost of hardly one rupee a person. The economic, political and social impact of this development will be so profound that it is difficult to measure the cost-benefits in

financial terms. This is an age of communication and in very few areas are there as many major breakthroughs as in the technology of communication. Yet most of the developing countries have hardly begun to exploit the potential of communication through space.

5. Resource Survey :
One important factor in economic planning is the identification and allocation of a nation's natural resources. Most of the developing countries have fragmentary, limited, and inaccurate data concerning their resources : forestry, minerals, animal wealth, water and even energy. Through remote sensing, explorations are underway to identify minerals in Egypt, ground water in Iran, and forests in the Philippines. At the International Seminar on the Benefits of Remote Sensing for National Development in the Philippines, April 1978, it was pointed out that for national development it was essential to discover and plan an assured supply of critical minerals. For such an exploration, it was emphasized, remote sensing through the Landsat program was an important tool. In short, for the first time, developing nations can have a continuous inventory of their critical resources for their development planning and accelerated growth. The UN Conference in 1992 on Environment and Development, would be an important event in bringing out a new plan for environment and sustainable development.

6. Medicine :
Bio-astronautics as a new science of life in space may have a great deal to contribute to our understanding and control of human illnesses. Already, a great number of medical applications of space industrialization are finding their way into our lives, such as a "laser cane" or automated body-monitoring devices. For developing countries, however, the problems of health and medicine are quite different and, at this stage, they fall into two categories : (1) Applying available medical knowledge to the control of diseases, particularly in the remote areas through locally-trained doctors as it has been done in the People's Republic of China, and (2) Inventing new ways to control tropical diseases, particularly those which defy the terrestrial research methods, by conducting researches in space. If these researches are planned during the 90's, they should have some results available by the end of this century. Major developments in this area are yet a decade away but their potential cannot be underestimated.

7. New Materials:
Besides mineral resources from the Moon and even from asteroids as emphasized by Dr. Brian O'Leary, the immediate promise of space manufacturing is the creation of new materials, some of which are already on the market. The less industrialized countries face two major problems, among others : a critical shortage of housing and a sustained supply of clean, potable water. Among the materials developed in space, the one which has great value for these countries is plastic, mortar - light, non-corrosive, highly resistant, virtually unbreakable, thin-walled and, above all, of low cost. This material can be a substitute for steel and for pipes for water, sewage irrigation and drainage systems. It will be of great use, particularly in the remote areas. Another material which is a product of space resarch development in Switzerland is a new construction material made of aluminium and plastic foam. It can be used for prefabricated housing. Although this and other such materials for building purposes are beyond the reach of most developing countries at present, produced en masse, such materials can provide a solution to the housing problem which defies all the cost considerations if the traditional materials such as steel, cement and bricks are to be used. The gigantic task of meeting the shortage of 150 million housing units in developing countries would indeed justify newer materials and techniques experimented in space.

8. Energy :
Most of the developing countries are starved of energy. India, at the mercy of foreign loans, is offered an assistance of 150 million dollars by Japan for the energy sector alone. Hopefully, considering the shocking differential of consumption between the industrialized and less-developed countries, one wonders where the real energy crisis is. The OECD countries used up approximately 48% of global primary energy whereas developing countries used 16%. An average farmer in Asia uses less than 1% of the energy consumed by an average American. For the majority of people in Africa, Asia and South America the major source of energy is firewood, which is being depleted so fast that in many parts of the world the loss of topsoil, the erosion of land, and desertification, have become serious threats to their eco-system and consequently to their survival.

Energy from space for the earthlings is still a long way off. A vast amount of research in the utilization of solar energy is

underway around the world. Through available solar devices, it is possible to meet at least 50% of their needs for cooking, drying, and even pumping in the villages of the third world. Simultaneously, other energy sources such as biogas and fossil fuels should also supplement needs. But none of these sources can meet the demands of industrial development at a reasonable cost. Hence, if solar power satellites can provide clean, perpetual and possible cheap energy to these people, a new thrust can be given to their development. From the available research the SPS seems a viable concept though it seems very expensive and twenty-five years away. But in time no other energy source seems more attractive and powerful than that of bringing large scale energy from the Sun perenially.

The greatest threat facing the third world development is the unprecedented militarization - now space militarization - pursued by the super powers. It is estimated that soon these countries may expend up to 70% of their space budget for military activities. If outer space is ever fully militarized, the security of developing countries and even the very survival of man on Earth will be threatened permanently. The only recourse for these countries is to pursue vigorously the peaceful use of outer space as has been done by the United Nations. That is why the second U.N. Conference on the Peaceful Use of Outerspace has been directed towards the developmental issues of the third world.

In short, for the countries of Asia, Africa and South America the urgent task is to set up their own space agency which will accomplish goals of important development for their people through space science and technology.

CONCLUSION

We are at the beginning of a new era, an era of solving the problems of Earth from space. Whether we like it or not, we are in space. Many of the Earth's problems which have defied solutions for centuries can now be solved with newer knowledge and more ingenious techniques developed in space. For many millenia, men took flight into space through mythologies, poetry, and fiction; the many possibilities of space are real, immediate and unexpected.

Space developments are more than an extension of technological civilization on Earth. They can help solve Earth's problems, but more importantly, by going in space we find a new place in the universe. The limited Earth cannot confine man forever. Possibly one day man will be able to put most industrial activities in space in order that he can enjoy the bounties of the Earth in their fullness. It is an insult to man's mind and his spirit that two-thirds of humanity suffers from poverty, deprivation and wretchedness, while enormous resources and opportunities lie idle in space. Beyond the finiteness of the planet Earth lies the universe which can provide an infinity of possibilities for man to search, discover, use and enjoy for billions of years to come. Here scientists, engineers, planners, and administrators have a new challenge. It is through the daring and determined efforts and struggles of all men that we shall bring the benefits of space to everyone on Earth. As the Soviet visionary said prophetically, "The Earth is the cradle of man, but man cannot stay in the cradle forever."

I_6 Economic viability of using the Moon to supply energy to Earth

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This paper summarizes the conclusions of work undertaken by a NASA-chartered task group with respect to the prospects for obtaining a large fraction of the Earth's electrical energy needs from lunar activity, and the feasibility of such activities being largely undertaken by the commercial sector.

The task group was created to consolidate and assess the Helium-3 Fusion power proposals principally originated by Dr. Gerald Kulcinsky of the University of Wisconsin, **(Fig. 1)** the Solar Power Satellite concepts originated by Dr. Peter Glaser, **(Fig. 2)** and their lunar-based counterparts principally originated by Dr. David Criswell of the University of California. **(Fig. 3)**

Descriptions of the three system concepts were summarized based on previously understood system definitions, and their performance placed on a common basis for comparison. The principal transportation and other needs of the concepts were defined, based on the premise that lunar materials will be predominantly used by the solar power alternatives.

A scenario and likely timeline for the research, development, deployment and operation of the three system concepts was developed. It spanned a five decade time frame to 2040. **(Fig. 4)**

An economic model was prepared to predict the financial factors applicable to mining, delivery, and use of Helium-3 likely to be necessary for fiscally responsible program planning. A recognized but unanalyzed factor in the model was the economic value of the volatiles produced as a by-product of the lunar mining for Helium-3. Later work indicates that the value of the hydrogen, oxygen, water, and other gases used on the Moon or delivered to low Earth orbit could be very substantial and perhaps even rival those for Helium-3, depending on the magnitude of the anticipated space activity level. These volatiles could thus add to the economic viability of the Helium-3 approach. Similar arguments can be developed for material by-products from construction of solar power generating facilities on the Moon.

The principal findings of the panel include :

1. Terrestrial electrical energy needs are not readily predictable, but the likely acceptable cost of energy over the long development time of any of the above candidates is not.

2. The Moon MUST play a role in the long term energy supply to Earth. While use of conventional fossil and fission nuclear power will continue to expand, their costs will rise due to increasing pressures to make them more environmentally acceptable. The result will be a climate receptive for alternative non-polluting power, and a price acceptance which may be sufficient for enabling the development of lunar sources.

3. A lunar facility will be required, probably manned, in order to undertake the development of any of the three systems. The emplacement and routine operation of such a facility is a prerequisite to undertaking power system activity, and must be funded by governments, not by the private sector.

4. All three appear to have time frames compatible with developing needs, and with those of likely return to the Moon and emplacement of a lunar facility to enable the construction of the systems.

5. The private sector cannot fund the development of any of the three systems by itself, since the capital required is so large, and the payback time so long. However, government development without a major role by industry is neither likely nor desirable. However, the private sector must have large and early roles in the definition of any program in this area for it to succeed eventually as a non-government activity.

6. An innovative form of government and industry cooperation must be implemented if any such far-reaching concept is to be successfully undertaken. One such possible relationship is described.

Concept Description
HELIUM-3 FROM THE MOON

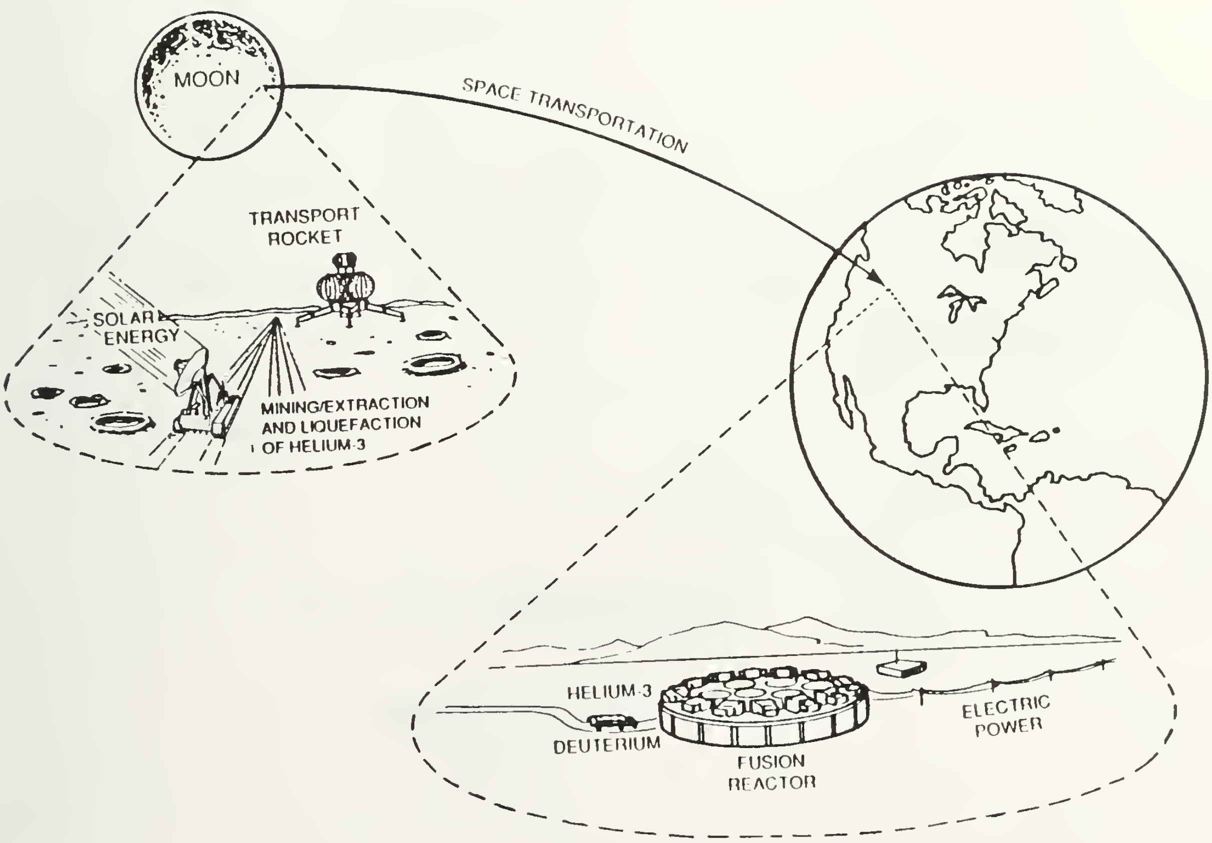

FIGURE 1

Concept Description
SOLAR POWER SATELLITES

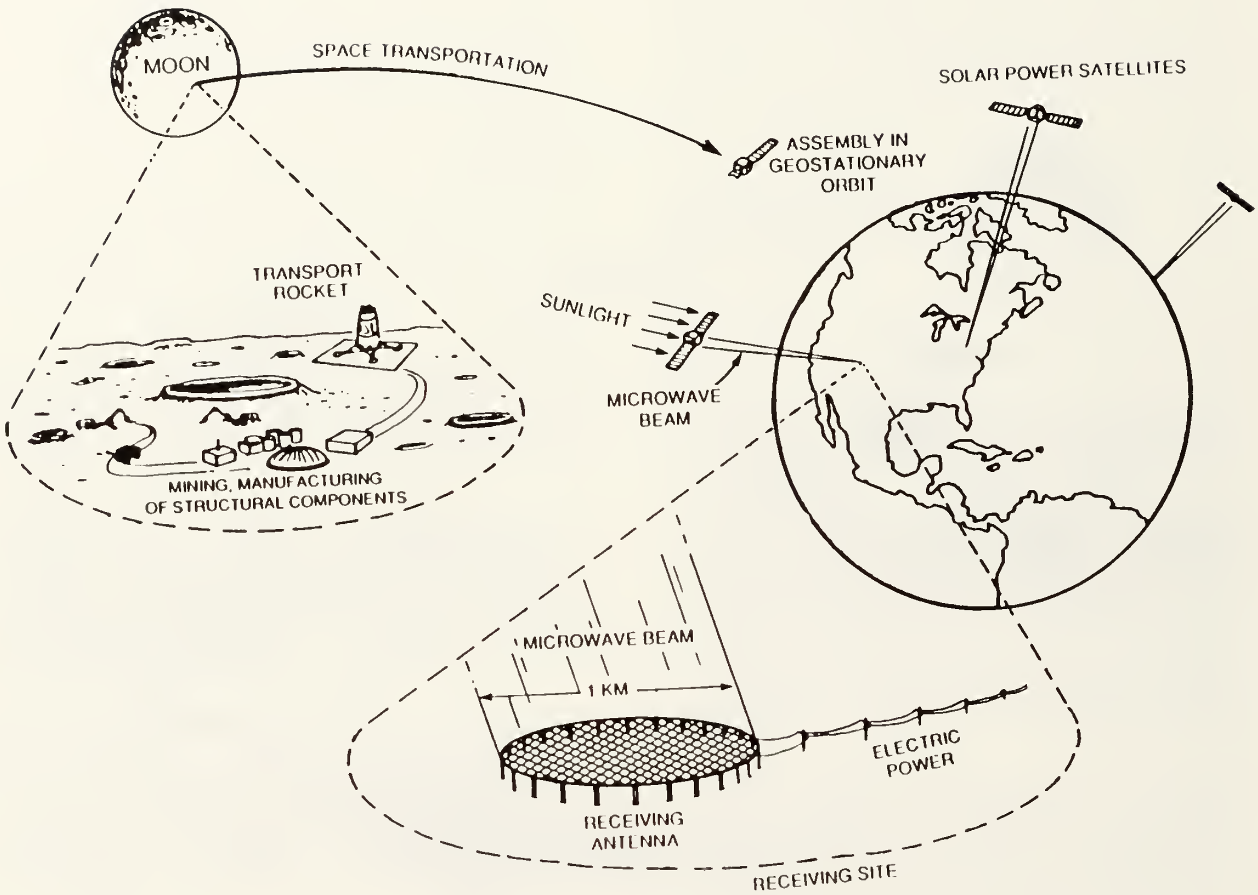

FIGURE 2

Concept Description
LUNAR POWER SYSTEM

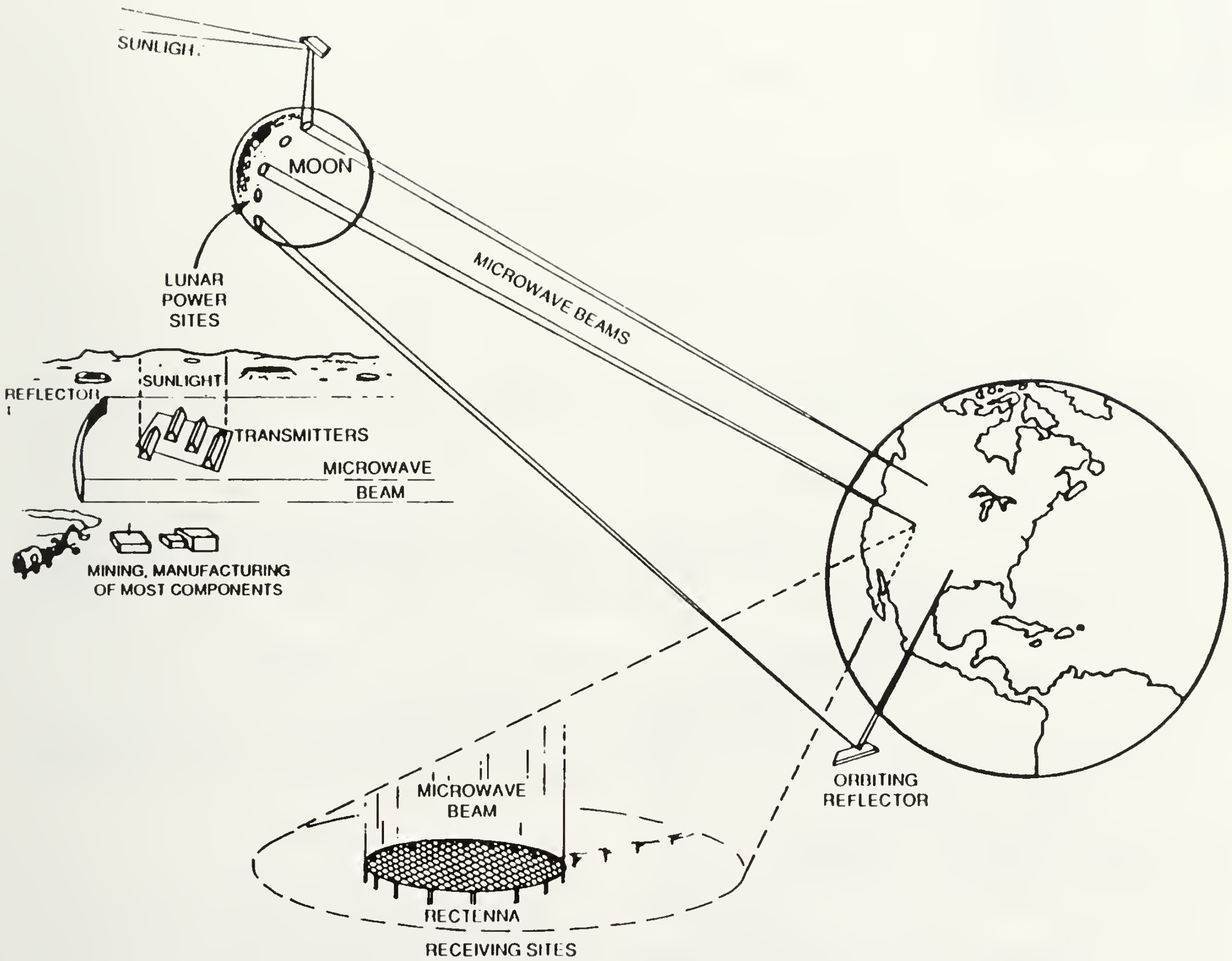

FIGURE 3

LUNAR BASE & ENTERPRISE CONCEPTS TIMELINE

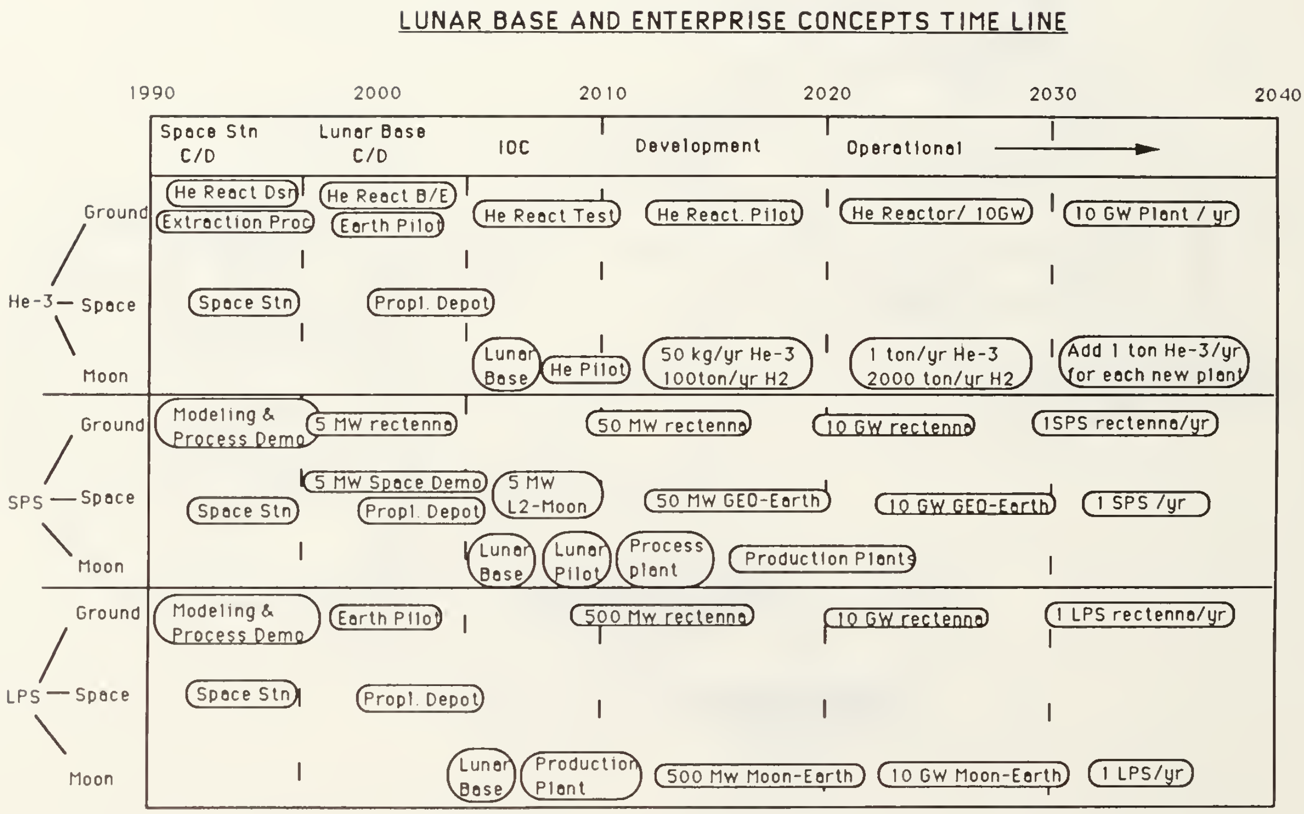

FIGURE 4

I_7 The Solar Power Satellites option re-examined

Peter GLASER - AD LITTLE, Cambridge, USA

Abstract

The rationale for converting solar energy in space for use on Earth on a global scale is examined. Advances in technology associated with solar energy conversion, microwave and laser beaming, and uses of extraterrestrial materials are discussed. A growth path for development starting with near-term demonstrations of power beamed to the evolving infrastructure in Earth orbits and the moon is outlined.

Keywords

Solar power satellite; solar energy conversion in space; microwave and laser beaming and conversion; applicable Earth orbits; use of extraterrestrial materials; societal issues.

Résumé

L'auteur examine les motivations essentielles d'une exploitation de l'énergie solaire spatiale pour une utilisation à grande échelle sur Terre. Il analyse les évolutions technologiques intervenues dans les domaines de : la conversion photovoltaïque les transmissions d'énergie par microondes et faisceaux laser, ainsi que les perspectives liées à l'utilisation des matériaux extraterrestres. Il présente un scénario de développement possible d'un système SPS depuis une très prochaine expérimentation de transmission d'énergie par microondes jusqu'au développement d'infrastructure en orbite terrestre ou sur la Lune.

Introduction

The exponential growth of the global population; projected to reach 8 billion by 2030 and the momentum required to satisfy the striving for acceptable living standards of this wave of humanity with largely unsatisfied needs, demand a speedy and effective global response to ensure that acceptable solutions can be developed in time.

The creation of the "Global Village" through worldwide communications media brings into sharper focus the disparities between populations in developed and developing countries. Energy use of populations in major regions of the world is related to living standards demonstrating that it will be increasingly more difficult to meet the rapid growth of energy use in developing countries by placing continuing reliance on conventional energy sources. As a result, there is growing concern that the planet Earth environment will not be capable of supporting the demands of an exponentially growing population.

The depletion of the Earth non-renewable energy sources although of potential long-term concern may no longer be the pacing issue. However, global warming, the result of strains imposed by industrialization required to achieve economic growth targets, are now recognized as a threat to the Earth's ecology.

To mitigate deleterious effects on the global environment changes in energy resource use on a significant scale will have to take place over several decades to make the transition to inexhaustible and renewable energy sources on a global scale. Because the time scale required for potential measures to mitigate global ecological deterioration and the effects of global warming are so protracted, it is urgent to start developing and selecting promising options now to sustain global economic growth without creating irreversible damage to the ecology.

As part of any assessment of alternative energy technologies, the potential use of extraterrestrial energy and material resources deserves to be seriously considered so as to provide an understanding of the inexhaustible space energy options available at various stages of global space development in the 21st Century. "Historically, wealth has been created when the power of the human intellect combined abundant energy with rich material resources. Now humanity can create new wealth on the space frontier to benefit the entire human community by combining the energy of the sun with materials left in space during the formation of the solar system."[1]

The challenge is not only to arrive at an unbiased assessment of viable options that can meet energy requirements at various stages of human development, but also to recognize that management of both renewable terrestrial energy sources and extraterrestrial resources for use on Earth will be required on a global scale. There is only a limited time measured in a few decades to achieve this goal. This calls upon a shared vision with a planning horizon extending well beyond the current one, and international cooperation to ensure humanity's progress in the 21st Century.

Humanity has reached a stage of development so that it can move beyond the surface of the Earth to access the inexhaustible extraterrestrial energy and materials resources in space. One possible approach, the solar power satellite (SPS), proposed more than two decades ago would convert solar energy in space for use on Earth to achieve global applications of baseload electricity, cost competitiveness with alternative energy technologies, compatibility with the environment, conservation of finite terrestrial resources and above all, benefits for society.[2]

The objective of the SPS is to convert solar energy in space and beam the energy in a suitable spectral region to the Earth to generate electric power continuously on a global scale for distribution to transmission networks. The concept of the SPS is not tied to any particular technology for beaming power from space to Earth, the magnitude of power delivered to Earth, a preferred design, the percentage of terrestrial or extraterrestrial materials used for its construction, deployment in specific Earth orbits, on the surface of the moon or on other planets. The key determinants for the realization of the SPS concept is the state-of-the-art of applicable technologies at various stages of their development, economic considerations, and societal issues including policies, regulatory guidelines, and above all the perceived value of meeting the growing energy demands of the global population in the 21st Century.

There is a growing consensus that the future uses of space resources will have the most profound effect on the civilization of the planet Earth, and that new knowledge, increased understanding, and enhanced scientific and technical capabilities will be essential to confront the challenges that must be overcome to achieve the inevitable transition to inexhaustible and renewable energy sources on Earth and in space. International cooperation will be highly desirable in moving towards this goal and in the process, a truly global civilization that will benefit all humanity can be created.

Technology Options For The SPS

The SPS is presently a very fertile field for innovation and many of the proposed novel concepts involve subtle advantages and disadvantages which may not be apparent without detailed analysis. Moreover, a change made in a particular subsystem often propagates throughout the SPS so that the consequences of the new technology cannot be evaluated without a complete system design study.

One useful approach is to consider the functions which must be performed in an operational SPS, instead of concentrating on specific engineering solutions. The primary system functions for any SPS, although these functions may overlap in some concepts, are: Collection of solar energy in space, conversion to an intermediate form of energy, transmission of energy to Earth, and reception and conversion to usable energy on Earth.

In addition, there are a variety of secondary functions, which must be carried out in order to make the SPS practical including: Space transportation from Earth to orbit, station-keeping and attitude control, assembly in orbit, power beam directional control, satellite maintenance, receiver maintenance, power conditioning and distribution aboard the SPS, power conditioning and distribution at the receiver, satellite thermal control, and ancillary functions at a receiving site location. Changes in the technical approach to perform the primary functions will have a major effect on the configuration, performance, and cost of the SPS; changes in the technologies employed to meet secondary functions may or may not have a minor impact.

There are several interrelationships between alternative SPS subsystems for meeting the functional requirements. Figure 1 shows some of the possible alternatives which have been considered as possible design choices. Any path through this diagram, from the general guidelines to the utility busbar, represents a conceivable SPS design. Paths which terminate represent technologies which are considered infeasible. For completeness, nuclear power alternatives have been included.

Many of the costs and benefits of new technologies are intangible, expressible only in incommensurable units. Examples are the laser power transmission system (LPTS), in comparison with the microwave power transmission system (MPTS). The LPTS allows changes in the optimum SPS power output; may reduce land-use problems but may require extensive long-distance power-pool interties to avoid weather outages. The relative importance to be assigned to these advantages and disadvantages is inescapably a matter of judgment, and any given assessment of power beaming technologies may be acceptable only when a shared common value system is evolved.

It may be possible to overcome these difficulties, by a two-stage process which explicitly recognizes that the primary requirement is not now to provide a definitive and reliable technical, economic and societal assessment of each technology option, but to investigate concepts which offer the greatest potential. The surviving concepts may then be subjected to more detailed analysis, leading eventually to preferred technologies for the SPS.

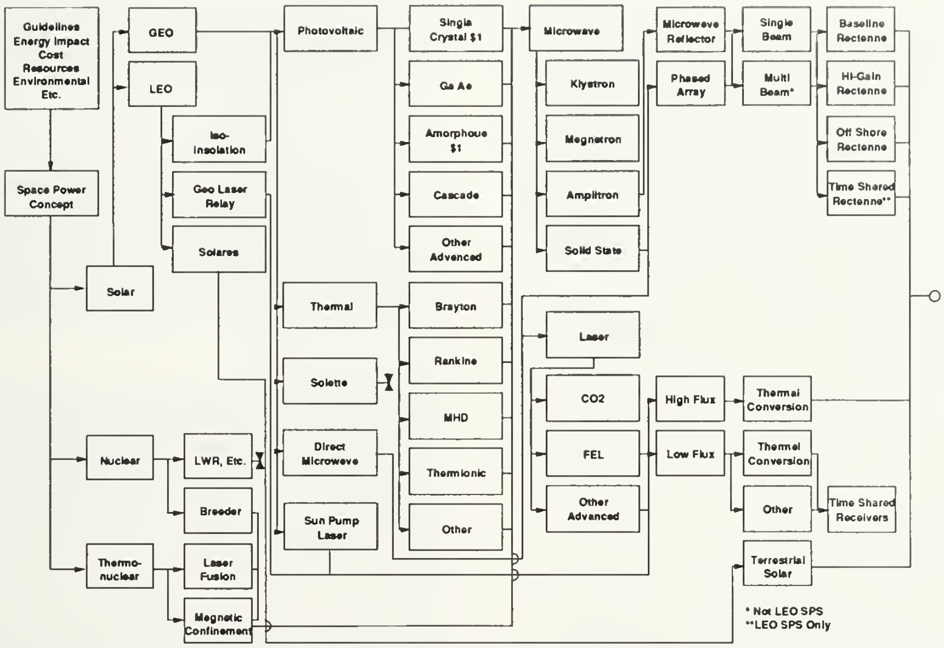

Fig. 1. Technology alternatives for space power systems.

Overview Of System Functions

Collection Of Solar Energy In Space

Solar energy conversion in the SPS can take a variety of different forms, including at least the following:

- An array of planar photovoltaic cells, with or without concentration.
- Mirrors to concentrate solar radiation to heat a working fluid in a thermal conversion system.
- Mirrors to drive thermionic conversion devices, photoklystrons, or sun-pumped lasers.

In most but not all cases, the unit power output of the solar energy conversion system is determined by diffraction and cost minimization considerations. The size of the solar collector is given by the efficiency of the overall energy conversion and transmission chain.

Most SPS concepts require conversion of solar energy to one or more intermediate forms before transmission to Earth. For example, a thermal conversion system may use solar radiation to store enthalpy in a working fluid, which is then converted to electricity by turbo-machinery, in order to operate power beam forming devices. The output of photovoltaic cells e.g.: advanced gallium arsenide solar cells, which convert solar radiation directly into electricity require power conditioning before feeding the electricity to the devices to form the power beam. Some direct solar energy conversion technologies, such as the photoklystron and the sun-pumped laser, contain an intermediate form of energy which use solar radiation to create a power beam without separate power conditioning and distribution.

There are several conceivable methods to transfer energy from space to the surface of the Earth:

- Microwave Power Beaming (MPB) was used in the SPS Reference System.(3)

  Microwaves can be converted to electricity with high efficiency, using one of the variants of the SPS concepts studied previously. Advances in microwave generation, transmission, and reception at frequencies higher than the 2.45 GHz already demonstrated, reaching to 35GHz, and beyond are worthy of consideration.

  MPB has the advantage that it is well understood, and offers the possibility of a high transmission efficiency (in excess of 60 percent, from DC in the satellite to DC at the utility bus). MPB uses the smallest solar array for a given power output, reducing array capital costs. If the SPS is in geosynchronous orbit (GEO), the unit power output tends to be higher than with other approaches, which implies a high front-end cost before the first SPS is operational. Remaining uncertainties regarding the long-term effects on terrestrial biota of exposure to low-level microwaves must be resolved before a MPB can be applied on a large scale, although studies on biota did not indicate any effects e.g.(4)

- Laser Power Beaming (LPB) has the advantage that diffraction is much less important at visible or infrared frequencies, therefore, LPB offers the capability of building the SPS, for example, in GEO with a unit power output at any level above about 10 MW.

  A wide variety of conversion techniques are conceptually feasible with LPB. Laser radiation may be converted to electricity by thermal or photovoltaic means, or by an array of dipoles and rectifiers scaled to the wavelength of the laser radiation. The laser radiation may also be concentrated and used directly as a source of heat, for industrial processes and other applications, e.g. to power aircraft after take-off and at cruising altitude, and prior to landing.(5)

However, the efficiency of the transmission system is likely to be considerably less than in the case of MPB, so that the cost per kilowatt increases. The beam flux density can be reduced to any reasonable level (if necessary, using concentration at the receiver) so that the beam will be environmentally safe. This approach would require a geographically dispersed network of receivers, with more receivers than satellites. The laser beams are then directed to whichever receiving sites are not cloud covered. The power is delivered to load centers by a terrestrial transmission system interconnecting the receivers. LPB is one of the most significant alternative technologies to microwave beaming MPB.

Alternative SPS Concepts

The following alternative concepts for SPS deserve further study including the following:

Gravity Gradient Stabilized SPS

The nominal attitude of the SPS solar array is perpendicular to the orbital plane. This is a position of unstable equilibrium under gravity-gradient torques, minimizing attitude control problems. An area penalty (9 percent) is incurred due to cosine effects, as the array does not track the Sun in declination. In addition, the beam transmitting antenna must rotate once per day about a single axis in order to track the receiving antenna requiring sliprings to transmit power. The gravity-gradient stabilized SPS is intended to overcome these drawbacks. In the preferred concept the SPS has a long axis which is nominally along the local vertical, with a fixed transmitting antenna at the bottom. Individual photovoltaic arrays are attached at intervals along the vertical axis, rotating about horizontal axes each day as the SPS moves in its orbit so as to remain perpendicular to the sun line. Libration in roll or pitch, is required to avoid shadowing of one array by another near local noon and midnight. Electricity produced at the arrays is fed to a solid state conversion microwave system. The central spine of the SPS contains a high-power waveguide into which the output of each array is fed. Power distribution is accomplished with microwaves rather than electricity which may be of advantage at large power outputs to reduce the mass of transmission lines.

Integrated Solar-To-Microwave Conversion

In this concept photovoltaic cells are attached directly to the back of a solid-state microwave beam transmitting antenna which is oriented permanently towards the Earth. A mirror system employing two reflections and affording some concentration (and perhaps spectral filtering to minimize thermal loads at the solar cells) directs sunlight to the photovoltaic array; one of the mirrors must rotate (about an axis normal to the GEO plane) to compensate for orbital motion. The direct connection between solar cells and microwave devices greatly simplifies power distribution. The rotating joint is part of the solar radiation collection system rather than a component of the electric power distribution system, so that no electricity conducting sliprings are required.

Station-Kept Arrays

The various subsystems of the SPS (solar collector, solar-to-electric conversion, electric-to-microwave or laser beam conversion, etc.) need not necessarily be physically connected, but could fly in formation, using high-specific-impulse thrusters to maintain spacing and orientation in the presence of gravity-gradient forces, torques and other perturbations. Several variants of this concept have been investigated, and the conclusion is that this may be a feasible option for the SPS.

Other factors being unchanged, the thruster specific propellant requirements (i.e., the propellant consumed during the lifetime of the system, divided by the system mass) for station-keeping and attitude control, and the thruster specific power (thruster power divided by system power output) all scale linearly with the satellite's dimension. Station-keeping designs may thus be more attractive for lower output power SPS configurations.

Iso-Insolation SPS

This concept, places the SPS in an iso-insolation orbit with the power beamed directly to receiving sites on Earth with microwaves. Because of the shorter range, much smaller power outputs (and hence receiving antenna areas) are possible. A sufficient number of SPSs can provide continuous power to a given receiving antenna if its latitude is fairly high e.g.: (Europe and most of the United States).

This system would be economic only when there are enough SPSs in orbit to provide baseload power to a given receiving antenna, and enough sites are available to provide a reasonable duty cycle for the SPS. Although the lower unit power output is an advantage, it may be difficult to construct economically credible buildup scenarios.

The Multibeam SPS

A complex phase-control system would allow a single transmitting antenna to feed several receiving antennas. For SPS power output optimization, the area of each such receiving antenna decreases as the square root of their number, while the areas of the transmitting antenna and the solar array increase in the same proportion. This technique may allow reduction of the power from each receiving antenna (and hence of its area) by a factor of at least three. Alternatively, several multibeam SPSs could feed one receiving antenna, maintaining the power output but reducing receiving antenna area without violating ionospheric flux density constraints. The multibeam approach may permit consolidation into a fewer number of larger SPSs, increasing orbital slot availability in GEO.

Lunar SPS

By the middle of the 21st Century the capacity of global electric power generation systems may have to be increased perhaps tenfold from the current levels. To meet such a huge power supply scenario the moon could be used for both solar energy collection and power beaming to Earth. Engineering and cost models indicate that a Lunar SPS may be technically and economically feasible by that time.[6]

Terracing An SPS Program

The development of an SPS program introduces technical, economic, and societal challenges and risks. These will have to be defined and assessed before possible technical options can be exercised on a limited or eventual global scale. A future global SPS system consisting of a spectrum of SPS technologies, and the supporting space and terrestrial infrastructure, represents a "program" that will extend over an extended time scale for implementation, yielding progressive and continuing benefits with no agreed-upon predetermined end-point at which the global

SPS system could be considered to be accomplished. Typical U.S. programs of a similar nature include the Interstate Highway Program, the National Space Program, the hydroelectric power development of the Tennessee Valley Authority, and global air transportation.

A "project" can be defined as an enterprise that, after the investment of time, effort and resources, would culminate in the accomplishment of specifically defined and quantifiable achievements. The Alaska oil pipeline, the Aswan High Dam and the Apollo Program "to land a man on the moon and return him safely to the Earth in this decade" and the Tunnel connecting England and France are typical projects.

Success or failure for such projects is related to whether or not their stated objectives were met within the agreed-upon budgets and on schedule. In practice, however, due to the length of time it takes to complete large projects, such projects are to varying degrees subject to changes in the administrative, legal and regulatory environment, as well as to changing economic and political conditions that can change the justification or otherwise modify the requirement for their continuation. The result has been that large projects require a complex and continuing consensus of public and/or private investors and sustained support of appropriate interest groups and government agencies during the various stages until completion.

Based on the various challenges associated with large projects a strategic option was identified that could overcome some of the barriers placed on projects with a high level of risk. This strategy is based on the concept of "terracing" a program such as a global SPS system (see Fig. 2).

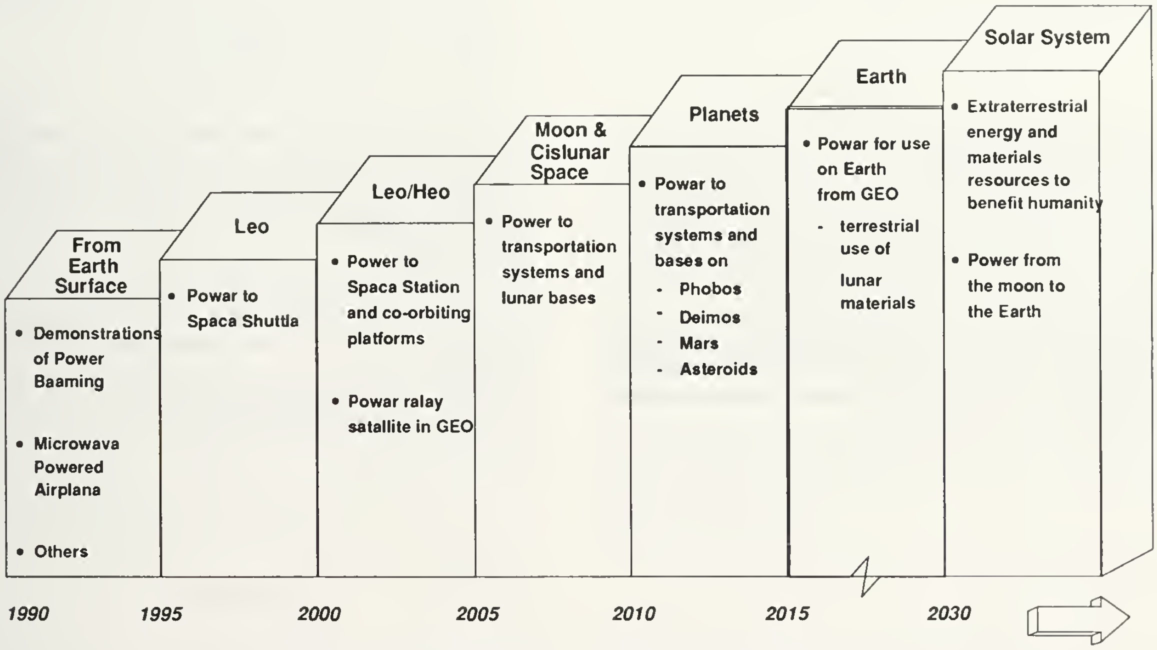

Fig 2. Terracing strategy for a global space power system.

"Terracing" is a strategy that could mitigate impediments associated with a project that relate to controlling it, termination (when warranted), technical uncertainties and risks, investor confidence, and the external environment. The terracing strategy concept permits a specific project to be viewed in part as a segment of a broader program, and planned to achieve a set of intermediate objectives. It assumes that specific but broadly applicable technical capabilities (generic technologies) will be developed as part of other related programs (e.g., renewable energy and space exploration), and associated specific projects (e.g. terrestrial photovoltaic installations and space station power generators), to provide an infrastructure which is essential to the success of the project and the eventual success of a program. The achievement of intermediate objectives of such a program is independent of the possible future success or failure of any particular project as long as failures to achieve specific objectives are analyzed, problems resolved and applied in subsequent projects. The "terrace" level which is reached is based on applications of generic technologies, which have the widest possible application and receive the support of one or more constituencies, and potential investors who may have no interest in or connection with a future project or a long-term program.

The benefits of terracing would vary from project to project but would strongly influence and drive the availability of generic technologies, clarify economic issues, and enhance the potential for resolving societal concerns at each successive terrace level.

Early demonstrations of power beaming provide a unique opportunity for international participation. Broad participation in such projects could lead to future cooperative efforts among the nations which expect to benefit from the power generated in space. International participation could also ease obtaining agreements regarding the use of orbits, portions of the electromagnetic spectrum, the applications of the power generated in space for use in space, and could lead to a consensus regarding

the future development of space power.

Groups in Europe (Eurospace), Japan (MITI), U.S. (Texas A & M) and U.S.S.R. (Moscow Aviation Institute) are engaged in planning space power demonstration projects. Some of these projects may be completed in the time frame of the International Space Year starting in 1992, others may extend over the next decade. The plans for these projects are diverse enough in the technologies to be employed for the demonstrations that important new data will be obtained to guide subsequent projects.

Consideration is being given to the possibility of new enterprises to supply power to elements of the evolving space infrastructure such as space stations and bases on the moon and Mars. The projects would also serve to establish policy and regulatory guidelines by appropriate national and international bodies to meet safety, environmental and regulatory requirements, and pave the way for the development of novel strategies to enable the realization of a global SPS system.

Conclusions

If the availability and attractiveness of fossil sources of energy were sufficiently diminished then development costs of renewable and advanced space solar energy technologies would be considered by the public a small price to pay to meet energy demands. Policy makers would have an easier task in stimulating industry to invest in energy-related development projects. Although technology is the genesis of policy a commitment by the public and private sectors to seek ways to cooperate could lead to sharing of risks and rewards associated with future energy projects such as SPS.

Both national and international energy policies should recognize that an SPS could be an important component of future energy supply options on Earth, and ways sought to enable an SPS system to contribute on a global scale. More and more of the world's work is being accomplished on an international scale regardless of political systems, or geography. Like all new societal trends, this proliferation of new possibilities will require changes in attitudes if this heightened power of accomplishment is to contribute positively to human welfare. Entropy remains an inescapable factor. As Georg von Lengerke Meyer said a century ago, "Things alter for the worse spontaneously unless altered for the better designedly."[7]

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A1.1 Satellite Power Systems - Promise and Perspective

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ABSTRACT

The future energy requirements of the Earth are discussed, together with the problems and possibilities associated with energy generation. If the total population is to increase, if the developing countries' standards of living are to improve, and if global warming as a result of fossil fuel combustion is to be avoided, radical changes must be made to the methods of energy supply. Such changes are considered, indicating the need for the development of new forms of renewable energy. The use of satellite power systems is discussed in this context.

RESUME

Les besoins énergétiques futurs de la Terre sont discutés dans le contexte des problèmes et des possibilités concernant la production d'énergie. L'augmentation de la population, du niveau de vie des pays en voie de développement et le non-recours à la combustion d'énergies fossiles à cause du réchauffement planétaire, devraient nécessiter des changements radicaux avec le développement de nouvelles filières d'énergie renouvelable. L'utilisation du SPS est discuté dans ce contexte.

Introduction

This paper discusses the future energy requirements of the Earth, and the problems and possibilities associated with energy generation. No attempt is made to forecast detailed energy needs, or the actual breakdown of energy sources. Such discussions would, most probably, be subjected to large variations and errors in the estimates. Rather, the commentary is kept general, to emphasise the main trends and ultimate requirements. These trends are inescapable and indicate the scale of the problems associated with future energy generation.

If the total population is to increase, if the developing countries' standards of living are to improve, and if global warming as a result of fossil fuel combustion products is to be avoided, radical changes must be made to the methods of energy supply. Ways of burning fossil fuels with higher efficiency and less emissions must be developed. Energy conservation techniques must be improved. Nuclear power must play an even greater role in energy generation. Forms of renewable energy other than hydroelectricity must be investigated and developed.

The use of satellite power systems is discussed in the latter context. These have the potential to provide an inexhaustible source of clean safe energy.

Future World Energy Requirements

The first step in estimating the future energy needs of the World is to estimate World population levels. Two recent papers by Lomer[1] and Wright and Rodliffe[2] have also treated

this subject, and are used as a starting point.

It is well established that in the "developed countries" population growth is relatively small, at less than one percent per year. In the "developing countries", however, the growth rate commonly reaches three or four percent per year, with population doubling times of 20 to 40 years.

The current population levels are 1.1 billion in the developed countries and 3.3 billion in the developing countries. There is widespread agreement, based for example on careful demographic analyses carried out by the United Nations and the World Bank, that the World population will increase to 1.4 billion and 6.4 billion, for a total of 7.8 billion people, by around the year 2020.

The UN has carried out predictions up to 2075, without publishing in detail the arguments for later years 3[3]. Figure 1 shows the UN predictions, with a split suggested by Lomer[1] to indicate the mixture of developed, developing and newly-industrialised countries. Even if one-third of the developing countries industrialised in 40 years, the rate of population increase in the developing countries must fall to the same rate as that found in the developed countries by the end of the century, if the shape of the overall UN curve is to be believed. Despite the lack of evidence to support this decreased expansion in the developing world, these population trends are accepted as an optimistic basis for future discussion.

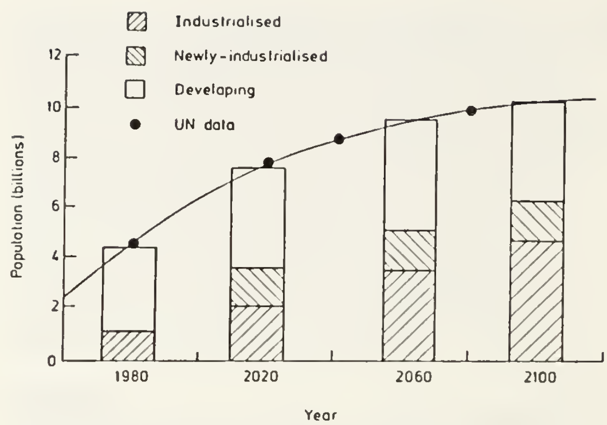

Figure 1 World population projections, from UN data assuming 33% of developing countries become industrialised in each 40 year period

Future World Energy Utilisation

The second factor to be estimated is the energy requirement per person, and this is the reason for differentiating between developed or industrialised countries and developing countries. At present, the total energy usage in industrialised countries averages 6 kW per person, while in developing countries it is only 1 kW per person. Electricity consumption in the developing world is very small, but represents 2-3 kW per person in the industrialised world and is rising rapidly as a fraction of total energy.

In the developed countries, economies have shown a steady growth over the years, and this growth has become the accepted norm. It is to be assumed that there will be continued pressure for economic growth in the developed World.

In the developing countries, an abundant supply of affordable energy is just one of many requirements that are needed for development. However, without such a supply of energy it is certain that economic development will be impossible. This is illustrated by Figure 2[2] where the real gross national product per person is shown as a function of energy use per person. It can be seen that a very good correlation exists.

The amount of energy consumed per person is influenced by how efficiently the energy is used and by the effectiveness of energy conservation measures. It is also influenced to some extent by whether the economy is a manufacturing or service one. Climate is an important driver, dictating energy needs for heating or for cooling (particularly important in future years as more developing countries in the tropical belt industrialise).

It is essential for the developed countries to decrease their usage of energy. Since the oil crisis of the 1970's this has happened, with

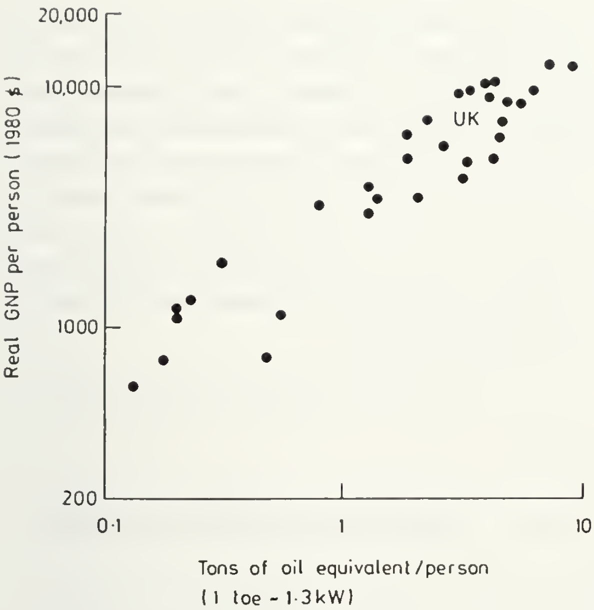

Figure 2 Gross National Product per capita as a function of energy per capita (1985 figures)

total energy usage decreasing and electrical usage increasing. Figure 3[1] shows how energy usage in the World would increase if optimistically the industrialised and newly-industrialised countries would halve their gross energy usage per person by the end of the next century. Two cases are shown, that for the industrialisation of one-third of all developing countries and that for the case of two-thirds industrialising.

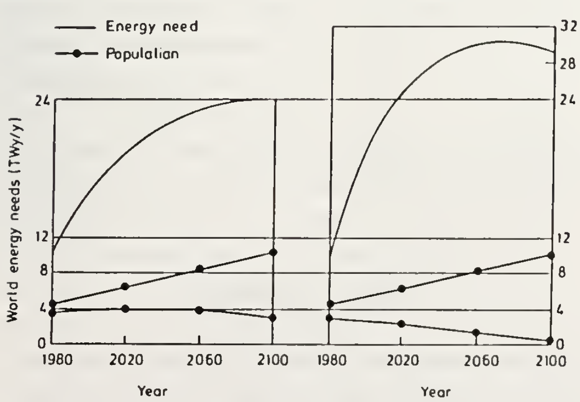

Figure 3 Total world energy usage projections over the next century

On these calculations there is no extrapolation that leads to a usage less than 2.5 times the current level of 10 terrawatt-years/year (TWy/y), and increases nearer to a factor of 3 seem more likely to be required.

The developed countries must learn to economise in order to teach the newly-industrialised countries how to economise even to achieve this result. If any potential economic growth was only just offset by improvements in efficiency, and the energy usage per person remained constant at 6 kW per person, and if newly-industrialised countries also used this same amount of energy, then total annual energy requirements would increase by about five times the current amount.

Such levels of growth would be hard to finance and to resource, and would lead to a pollution load that would be difficult to absorb. In addition, countries will not switch from developing to fully industrialised overnight. Nevertheless the standard that should be aimed for in the developing World is important. Unless massive additional energy conservation measures turned out to be effective, to have less than twice the current rate of World energy consumption would seem to constrain the rate of development of non-industrialised countries to below the rate of development currently being achieved. This is surely unacceptable.

Future World Energy Supply

The next question to be answered is that of future energy supply and energy sources. At present, nearly 90% of the World's needs are supplied by fossil fuel, with the remainder being met almost entirely by hydropower and nuclear energy. Wright and Rodliffe[2] examined how these contributions could be expanded to meet the growing demand.

Fossil energy usage is likely to be constrained by the emission of carbon dioxide and the greenhouse effect. The level of CO_2 in the atmosphere has grown steadily over the last century, from a level of 270 parts per million (ppm) to the present level of 350 ppm. It is currently rising at 0.4% per year.

The global geochemical system is not capable of accommodating fossil fuel combustion products at the current rate of production. Fossil fuel consumption should be reduced, rather than increased. Figure 4[2] shows a prediction of CO_2 levels, for different rates of increase or decrease in fossil fuel use. In order to stabilise CO_2 levels, it is necessary to reduce emissions to the atmosphere by about 1% per year.

Although it is possible that techniques may be developed which economically remove CO_2 from combustion products, the engineering problems are severe and the current options appear very costly. Wright and Rodiiffe[2] estimated that it was likely that fossil fuel burnt in 2025 would lie between 70% and 100% of current global levels ie. between 6-9 TW. This, of course, implies a significantly cleaner burning process.

Of the renewable energy resources, hydropower is responsible for by far and away the greatest contribution, providing some 7% of current energy needs. Surveys have been made of the further potential for hydroelectric development. It appears that the cheapest and most environmentally acceptable schemes have already been developed. Nevertheless the pressure on energy resources is likely to lead to further development of hydroelectric power, the ultimate resource being estimated at about 1.5 TW. A reasonable assumption, then, is that the hydroelectric contribution will lie between its present level of 0.7 and its ultimate level of 1.5 TW.

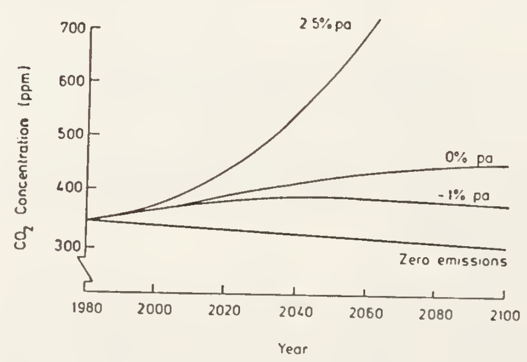

Figure 4 Atmospheric carbon dioxide concentrations for a range of CO_2 input scenarios

A further contribution will be made by nuclear power. Wright and Rodliffe[2] noted that, although greater contributions are possible, it would seem reasonable to postulate a feasible World nuclear capacity of between 1-2 TW by 2020-2030. The larger programme would be supplying 17% of the primary energy needs. Nuclear power currently provides 11% of the primary energy needs in Western Europe and as much as 27% in France.

The energy supply situation is summarised in Table 1

Table 1.1 Present and Future Energy Supply

Source	Present (1989)	Future (2025) Low	High
Fossil	9.0	6.0	9.0
Hydroelectric	0.7	0.7	1.5
Nuclear	0.3	1.0	2.0
Total	10.0	7.7	12.5
Energy need	10 TW	20 TW	25 TW

It is clear that these sources of energy are inadequate to meet requirements even if the developing countries were to stay at the present low levels of energy demand per person, especially with the optimistic assumptions behind the figures (relatively limited population growth and a halving of industrialised energy consumption). The projected energy availability is grossly inadequate if the economies of the developing countries are to expand at even the present low rate of growth.

The Way Forward

The above, generalised, arguments are not meant to provide accurate figures for forecasts of energy supply and demand. Rather, they illustrate the basic problem facing the World.

If the total population is to increase, if the developing countries' standards of living are to improve, and if global warming as a result of fossil fuel combustion products is to be avoided, then radical changes must be made to the methods of energy supply.

Some of the most obvious and immediate responses to this situation are:

- the per capita use of energy must be reduced, by up to one half
- energy conservation techniques must be improved
- methods of burning fuels with higher efficiency and less emissions must be developed
- nuclear power must play an even greater role in energy generation, and new sources (fast reactor, fusion) must be developed
- forms of renewable energy other than hydro-electricity must be investigated and developed

To focus on the latter point, the use of renewable energy, one overriding factor has to be kept in mind. That is the sheer scale of the problem. The above discussion argued for extra energy needs of at least 12 - 14 TW, on very optimistic assumptions. This represents a more than doubling of the current global energy production. It is difficult to see sources of Earth-based renewable energy that can provide even a fraction of this requirement with out serious and probably unacceptable, effects upon the environment.

One alternative technology for energy production is that of space-based solar power. Sunlight is converted in space to power, and this is then beamed back to a receiving point on the surface of the Earth. This could give, in principle, an inexhaustable source of clean safe energy. Previous studies have shown, although admittedly using simple models, that the use of space for power and resources can eliminate all restrictions and limits to growth[4].

Since the suggestion by Glaser[5] of the satellite power system concept, there have been many studies carried out in this area. It has been demonstrated many times that space power could provide the needs of the Earth for the forseeable future. However, many of the scenarios evolved during the 1960's and 1970's were grandiose in nature and did little to aid promotion of the concept.

This is only one of the many problems with, and qualifications to, the goal of inexhaustible power from space. The concept of satellite power systems must be put into the perspective of today:

- the cost of generating electricity in space must be reduced by at least a factor of 10,000 over current day costs
- a complete space infrastructure must be created to support the endeavour, with regular low-cost access to space as a component
- the size of satellite power systems must be much smaller than previous designs in order to reduce the requirements placed upon launch systems
- the public perception of safety in energy generation, and support for high technology solutions, must be changed; in the era of Bhopal, Challenger and Chernobyl this will not be easy.
- implicit in the last point is the need for mankind to move away from an Earth-centred outlook, to encompass the philosophy that Earth is only a small part of the resources available
- the timescale to achieve these goals is short, but realistic targets must be set for the creation of a space-based energy supply.

These comments must be viewed in the light of the alternative situation, of an energy famine of a large magnitude with consequent restrictions upon growth of the industrialised societies and denial of such a way of life to many non-industrialised countries.

Ways and means must be found to take satellite power systems from concept to reality in order to benefit all the peoples of Earth.

Acknowledgement

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A1.2 Terrestrial and space power systems: Life - cycle energy considerations

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ABSTRACT

This is a brief review of the net energy of various actual and proposed large scale power systems. Clearly space-based systems that tap solar energy can deliver far more net energy to Earth than solar systems based on Earth or terrestrial systems that tap non-renewable resources. It is reasonable to expect that microwave rectennas will provide more net energy output than conventional power stations or anticipated fusion reactors. The major uncertainties are noted in the net energy calculations for the three power options that use lunar resources (He^3, lunar derived SPS, and Lunar Power System).

RESUME

Cet article présente une revue du rendement énergétique net de différents systèmes de production d'électricité, actuels et futurs. Il apparaît clairement que des systèmes de conversion de l'énergie solaire établis dans l'espace ont un rendement net bien plus élevé que leurs homologues terrestres, ou que des centrales utilisant des sources non renouvelables. On peut raisonnablement s'attendre à ce que les antennes réceptrices aux microondes aient un rendement énergétique net supérieur à celui des centrales conventionnelles ou des futurs réacteurs à fusion. Les principales incertitudes sont notées dans les calculs de rendement net en énergie des trois options qui utilisent les ressources lunaires (He^3 : Centrale Solaire de Puissance option lunaire et Centrale Lunaire de Puissance).

Terrestrial Systems and SPS

During the late 1970s the United States Department of Energy supported work to estimate the net energy payback of terrestrial power systems and space-based solar power systems (Cirillo et al. 1980). Table 1 summarizes the results :

	Coal		Nuclear	Terrestrial	Solar(1)	SPS (ref)	
	AFBC	CG/CC	LWR	Thermal	Photovoltaic(2)	Silicon	GaAlAs
Parameter Gross Efficiency(3)	28.1%	36.7%	21.7%	11.4%	5.7%	7.0%	6.9%
Operating Efficiency(4)	26.7%	33.4%	20.4%	11.4%	5.7%	7.0%	6.9%
Operating Ratio(5)	5.3	3.7	3.3	26.7	27.3	16.7	77.9
Lifetime Efficiency(6)	26.4%	33.0%	20.3%	11.3%	5.4%	6.9%	6.9%
Lifetime Ratio(7)	4.4	3.3	3.0	11.5	1.4	3.9	18.0
Payback Period (Electric Basis), Yr.(8)	1.3	1.1	1.1	1.5	19.8	6.4	1.3

Table 1. Net Energy Indices of Terrestrial Power System and SPS

(1)	The data for the solar energy systems are limited and, in some cases, highly uncertain; conclusions should be drawn with caution.
(2)	Silicon system (single crystal, thick cells)
(3)	Gross Efficiency = Annual Net Output/Annual Primary Input = NO/PI NO = Net Output (Joules) PI = Primary Energy Input (Joules) (ie. basic energy resources)
(4)	Operating Efficiency = Annual Net Output/(Annual Primary + Operating + Internal Inputs) = NO/(PI + AOI + IU) AOI = Ancillary Operating Inputs (Joules) IU = Internal Use (Joules)
(5)	Operating Ratio = Annual Net Output/(Annual Operating + Internal Inputs) = NO/(AOI + IU)
(6)	Lifetime Efficiency = Lifetime Net Output/(Lifetime Primary + Operating + Internal + Capital Inputs) = T*NO/[(T*(PI + AOI + IU) + CI] T = System Lifetime (Years) CI = Capital energy inputs (Joules) (from Earth)
(7)	Lifetime Ratio = Lifetime Net Output/(Lifetime Operating + Internal + Capital Inputs) = T*NO/[T*(AOI + IU) + CI]
(8)	Playback Period (time at which Net Output = Operating + Capital Inputs) = (AOI + CI)/NO

Table 2. Footnotes and Definition of Terms in Table 1

Gross Efficiency is of greatest concern when a power system is being used to extract energy from a non-renewable resource. Emphasis is on extracting the greatest fraction of usable work from the resources. The index does not intrinsically differentiate between renewable and exhaustable resources. Coal, nuclear, oil and many other terrestrial systems tap non-renewable sources of primary energy. Terrestrial solar thermal and photovoltaic and SPS tap non-terrestrial sources that are effectively infinite as far as the present needs of Earth are concerned. They provide net new high-quality power to Earth.

The Operating Ratio specifies how much energy the system outputs over its life compared to how much energy must be input to create the system and to keep the system running. The inputs include the energy to produce the plant, as averaged over the life of the plant, and the energy used to keep internal processes going (ie., ash and sludge recovery and maintenance and cleaning). Thus, this index is a measure of the ability of the system to amplify its secondary energy inputs of operation and maintenance and internal energy loops. Notice that the the GaAIAs SPS is projected to multiply the secondary energy inputs by a factor of 77. This represents a net gain in quality energy to Earth.

The Lifetime ratio is the integral of the Operating Ratio over the life of the system adjusted for the energy to manufacture the system. Thus, the Lifetime Ratio is lower than the Operating Ratio. An advanced coal-fired plant will only amplify its Lifetime energy input by a factor of 4.4. An advanced GaAIAs SPS will return 18 times as much quality energy to the Earth as was used to create and maintain it. The GaAIAs SPS provides a net increase in quality energy for use on Earth.

The Payback Period is the time for the system to return the sum of its energy of construction and maintenance. Notice that solar photovoltaic systems that use single crystal silicon solar cells require a major fraction of their system life to return their energy of manufacture. Newer thin-film technologies can significantly decrease this factor. It is important to remember that coal and nuclear systems deplete finite energy stores on Earth whereas the terrestrial and space solar systems introduce net new energy to Earth.

The performance ratios of both the terrestrial solar systems are over-stated by a factor of 2 or more if they are the primary providers of energy to a region. These systems are scaled to provide day-time and early evening power in concert with other existing conventional systems. They scale up considerably in size to provide overnight power, power distribution, and power for indeterminately long periods of cloudy weather. Extensive facilities for power distribution and storage can quickly mount in expense to exceed that of the primary power source.

Holdren et al. (1988) provide and independent estimate, Table 3, of the

Energy System	Ton of Materials per GWe-Y Total Metals	Energy Metals GWt-Y per GWe-Y	Tons of Materials Concrete	Energy GWt-Y per GWe-Y Concrete	Total Materials GWt-Y per GWe-Y	Fuel (as ore) Tons	Fuel Losses GWt-Y/ GWt-Y out	Total GWe-Y Output per GWt-Y input
Coal *low*	1000	0.0030	5000	0.0006	0.0036	3,500,000	0.07	13.4
Coal *high*	2000	0.0060	7000	0.0008	0.0068	3,500,000	0.07	12.8
Fission *low*	1000	0.0030	8000	0.0009	0.0039	200,000	0.18	5.4
Fission *high*	2000	0.0060	13000	0.0015	0.0075	200,000	0.18	5.3
Hydropower *low*	1000	0.0030	13000	0.0015	0.0045	0	0.00	221.9
Hydropower *high*	2000	0.0060	70000	0.0080	0.0140	0	0.00	71.3
Wind *low*	5000	0.0151	6000	0.0007	0.0158	0	0.00	63.3
Wind *high*	15000	0.0453	50000	0.0057	0.0510	0	0.00	19.6
Fusion *high*	2000	0.0060	10000	0.0011	0.0072	3,500	0.00	139.1
Fusion *low*	4000	0.0121	20000	0.0023	0.0144	3,500	0.00	69.6

Table 3. Materials and Energy Inputs to Power Systems

primary materials inputs to conventional power systems and proposed (D-T fusion) power plants.

The Holdren et al (1988) data are combined with that of Cirillo et al (1980) to estimate the external energy inputs required to convert raw materials into a power plant. We also calculate the energy required to mine, transport, and process the respective fuels before their combustion or reaction to provide 1 GWe-Y of output. It was assumed that 26.5 kW-H/kg of energy is needed to produce and use steel in final form and that concrete requires 1 kW-H/kg for processing to final form. The mining, transportation, and final processing of coal and uranium are respectively 1.78 E-1 and 7.89 kW-H/kg of raw ore. The uranium estimate includes storage and transportation of radioactive fuel wastes.

Compare the last column of Table 3 to the Operating Ratios for coal and fission in Table 1. The Table 3 values are consistently higher because they leave out the energy costs of maintenance and internal energy loops. It is reasonable to anticipate that the actual Lifetime Ratio for fusion will be considerably less than the 70 to 140 shown in Table 3. The challenge in all future energy systems is to introduce a net flow of quality energy to Earth at the least expenditure of energy and materials on Earth.

Lunar Power System (LPS)

Criswell (NASA 1989) and Criswell and Waldron (1990, 1991a & b) have modelled the Lunar Power System and estimated the net energy payback. The results in Table 4 apply to an LPS scaled to "1990s" technologies in power collection and transmission and in the productivity of the machines that manufacture the lunar components. The key LPS engineering assumptions and inputs to Table 4 are in Table 5.

Gross Efficiency is a function of the conversion efficiency of the solar convertors and microwave generators. Ten per cent efficient solar cells are assumed in this example. Much higher efficiency, thin-film solar cells will be available in the next century. The primary effect of higher cell efficiency is to reduce the amount of chemical processing required to make the power collection wires that connect solar cells to the microwave generators. Production of solar cell cover glass is a secondary consideration. Greater conversion efficiencies than shown in Table 5 will sharply increase all the ratios in Table 4 and decrease the already small Payback Period.

Even the relatively modest efficiency assumptions in Table 5 indicate that the reference LPS has higher values for the Operating and Lifetime Ratios than any of the systems in Table 1. The electrical energy needed to launch materials from the Moon into orbit about the Moon and to make the large area solar collectors from thin-sheets of glass and thin-films for conversion of sunlight to electricity determine the net energy-related Operating Ratio and Lifetime Ratio.

Parameter	LPS Moon Collectors	Earth Rectenna
Gross Efficiency (3)	1.2 %	1.1 %
Operating Efficiency (4)	1.2 %	1.1 %
Operating Ratio (5)	303.2	174.9
Lifetime Efficiency (6)	1.2 %	1.1 %
Lifetime Ratio (7)	202.3	89.6
Payback Period (Electric Basis), Yr. (8)	0.10	0.33

Table 4. Net Energy Indices of Reference LPS

EXAMPLE LPS DATA **One 5 GWe Beam**	**Moon/Space**	**Rectenna**
NO	1.54E + 17	1.45E + 17
PI	1.31E + 19	1.38E + 19
AOI	2.54E + 14	1.38E + 19
IU	2.55E + 14	3.95E + 13
T	60	60
CI	1.52E + 16	4.74E + 16
Rectenna beam-filling (LPS/SPS)		2.50E + 00
Fraction of SPS Rebuilt over life		5.00E - 01
Solar Cell Efficiency		1.00E - 01
Wire Network Collection Efficiency		9.00E - 01
Electric to Microwave Conversion		4.00E - 01
Reflector Efficiency		9.50E - 01
Beam Efficiency (derived)		9.90E - 01
Average Atmospheric Transmission		9.50E - 01
Rectenna Output Efficiency		9.50E - 01
Overall Efficiency (busbar power/ continuous sunlight)		1.05E - 02

Table 5. Data for LPS Reference System

The dominate process energy in producing lunar surface arrays is thermal melting of lunar soil to make thin cover-glass and to make microwave reflectors. This thermal energy is not counted in the results shown below since it can be provided with very low mass solar thermal concentrators. The second highest uses of electricity are in the manufacture and assemble of microcomponents and in the refining of lunar iron to make the wire that collects the solar electric power.

The productivity of the machinery on the lunar surface is important. The energy cost of transporting components, production machinery, and people to space from the Earth is of secondary importance. Much of this energy expenditure for transport from Earth is avoidable by making portions of the lunar production system from lunar materials.

Approximately 10 % of the net energy of the space systems of the reference LPS is devoted to the transport of materials from the Moon to low orbit about the Moon (LLO) to construct orbital reflectors. These reflectors redirect sunlight to lunar bases during local morning or evening and during the eclipse of the Moon by the Earth. The reflectors are assumed to have a mass of 10 tons/km^2. Lighter weight mirrors would reduce this energy penalty. The orbital mirrors increase the energy efficiency of surface solar cells by introducing additional sunlight. The mirrors become more effective as the solar cells cover a greater fraction of the area of a base. Total area of mirror surface in space is initially proportional to the diameter of the transmitting aperture of a typical lunar base.

Waldron and Criswell (1991) discuss the use of additional power collectors across the lunar limb from the primary solar collector and transmitter regions. High tension transmission lines deliver the power to the Earthward transmitters. An LPS based entirely on the Moon would require approximately 3 hours of energy storage during full eclipses of the Moon by the Earth. Such eclipses occur approximately once per year. The energy to construct such energy storage is not included in Tables 4 or 5. The power storage could be located on the Moon, on Earth, or a combination of both planets.

Notice in Table 5 (ie. CI) that the rectenna is the dominant energy component of the LPS. The rectenna is identical to the reference system for the 1970s SPS. However, the large aperture transmission system of the LPS provides a generally uniform level of illumination across the rectenna. Thus, at equal peak intensities of the microwave beam the LPS rectenna outputs 2.5 times as much power as the reference SPS rectenna. In both cases the peak intensity of the microwave beam is assumed to be 230 watts/m^2. The rectenna can accept far more power with no major changes in construction technique or cost of construction. Thus, far more intense beams might be supplied to isolated areas, such as ocean atolls. If so, then the energy payback time of the rectenna might be a few weeks rather than the 4 months shown in Table 2.

Advanced Solar Power Systems (ASPS)

The GaAIAs SPS listed in Table 1 is representative of a very low mass design that may be achievable with terrestrial or lunar materials. Glaser (1989) maintains that mass-to-power ratios the order of 5,000 Tons/GWe output on Earth may be achievable. Presumably the ASPS (advanced) might also support near-field operation of the power transmission system and thereby make a factor of 2.5 better use of ground rectennas. The GaAIAs Operating and Lifetime Ratios in Table 1 might be increased by approximately a factor of 2 and the Payback time decreased by a factor of 2. Detailed modelling is necessary to confirm these estimates. It is not clear at this time that ASPS could achieve the Operating, Lifetime and Payback values of LPS even if its materials are ejected from the Moon rather than the Earth. This is because the energy that goes into launching the ASPS materials could instead go into launching machines of production to the Moon. A set of machines on the Moon can implace far more power in less than a year than could be generated by that mass of material arranged into an ASPS. Also, the lunar machines could keep emplacing power for approximately the lifetime of a satellite.

He3 Power System

Nuclear fusion of D-T and D-He^3 will likely use generally similar reactors. Notice in Table 3 that the range of estimated mass and energy inputs to the fusion plant are of the same general range as that of hydroelectric facilities. The fusion estimate presented in Table 3 applies to a D-T cycle in which the neutron flux does considerable damage to the inner wall of the fusion chamber. It is highly likely that the inner wall will have to be changed several times during the life of

the plant. If D-He^3 fusion can be attained on Earth with minimal production of neutrons then the primary reaction products are protons and He^4. They are both electrically charged and will do far less damage to the first wall. However, the D-He^3 plant will likely require a much larger vacuum chamber for the same level of power output. Thus, the D-He^3 reactor may be considerably more massive and input-energy intensive.

He^3 is present in the lunar soils at approximately the 10 parts per billion (ppb) level by weight. He^3 can be thermally extracted from lunar soils in terrestrial laboratories. Kulcinski et al (NASA 1989) have suggested that mining operations be established on the Moon to extract the He^3. The He^3 is returned to Earth and burned in an advanced fusion reactor (D-He^3 fuel combination). The He^3 system divides into a lunar portion and the fusion reactor on Earth. Table 6 provides a very rough estimate of the energy indices. The data estimates in Table 7 are from NASA 1989 (page 107), 1988 (pages 144-145). There are considerable uncertainties concerning the extractable supply of He^3 on the Moon and the feasibility and efficiency of future fusion reactors. The above predictions are not definitive. Table 3 contains low and high estimates of the net energy ratio for fusion reactors. Multiplying against a plant life of 30 years yields an approximate Payback Period of 2 and 4 years. These are considerably longer than in Table 6.

Parameter	He^3 Moon Collectors	Earth Reactor
Gross Efficiency (3)	60.0 %	60.0 %
Operating Efficiency (4)	58.9 %	42.8 %
Operating Ratio (5)	32.7	1.5
Lifetime Efficiency (6)	58.7 %	42.8 %
Lifetime Ratio (7)	27.6	1.5
Payback Period (Electric Basis), Yr (8)	0.12	0.01

Table 6. He^3 Net Energy Indices

EXAMPLE DATA FOR He^3 10 GWe Output	Moon/Space	Rectenna
NO	3.16E + 17	3.16E + 17
PI	5.26E + 17	5.26E + 17
AOI	1.77E + 15	1.47E + 14
IU	7.89E + 15	2.10E + 17
T	20	30
CI	3.53E + 16	4.40E + 15
He^3 Power System Assumptions		
Total Power Production (GWe)		10
Conversion Eff. He^3 to Power		0.6
Lunar He^3 Concent. (ppb)	8.4	
GWs to Process 1 GW-Y He^3	0.025	
Mass per miner (tons)	43.6	
Miners/GWe-Y	1.62	
Mass of Mining Equip (Tons)	1,178.08	
Earth-to-Moon energy (Joules/Ton)	3.00E + 13	
Fusion Reactor Specific Energy (J to make/J of He^3 Fusion)	0.008375	

Table 7. Assumptions concerning He^3 Net Energy

Lunar He^3 is a non-renewable resource. That is why the Operating and Lifetime Ratios for the reactor in Table 6 are so small. It may be that the best use of He^3 is to power large systems that are out of range of beamed power from the sun. The Operating and Lifetime Ratios for the lunar mining of He^3 are high. The primary energy input is the launching of the miners from Earth to the Moon. The solar thermal energy required to extract the He^3 is not counted. There is great uncertainty concerning the mass of equipment necessary to mine the lunar regolith and extract He^3. Some estimates indicate the mass of equipment might be ten times that assumed above. The LPS also requires soil excavation, beneficiation, and heating. LPS machinery assumed to produce the estimates in Table 4 is approximately 1/10th the specific productivity (tons equipment/(tons product/Hour)) of comparable machinery assumed for He^3 extraction in Tables 6 and 7. A factor of 10 increase in LPS equipment productivity would significantly increase the LPS Operating and Lifetime Ratios.

The concentration of extractable He^3 and the fraction of net energy output from a He^3 fusion reactor are highly uncertain. Large scale demonstrations are required on the Moon (mining) and on Earth(reactor). The reference to the specific energy of a fusion reactor (GJ output per kg of reactor equipment) in the reference NASA (1988) is unclear. The primary reference for this figure of merit must be examined (Bünde, 1985).

Economics and Net Energy

Net energy is not necessarily the decisive index in selecting a power system. There are other major considerations. These include such factors as : ratio of potential energy to total energy to be used, cost of establishing the plant, cost of operating the plant, costs of the total system to obtain and deliver power, and certainty of supply of the primary energy supply. Labor and fatalities per unit of energy produced are also important.

Table 8 summarizes a recent study by Criswell and Waldron (1991b) in which the costs and labor associated with various power systems were extracted from recent literature. The mass and equipment tonnage for LPS and advanced SPS relates primarily to the rectenna on Earth. It is clear that LPS and ASPS have considerable advantages over conventional terrestrial systems. These surprising advantages are a direct result of the rectenna being the major cost component. The simple rectenna delivers high power output per unit mass and per unit area.

Power Plants	**Labor Work-Y**	**Capital 10^6\$**	**Equipment tons**
Fossil (advanced coal)	260	200	10,000
Fission (advanced nuclear)	800	250	41,000
TTSP (Terrestrial Power Tower)	1,500	470	314,000
TPSP (Terrestrial Photovoltaic)	3,100	760	434,000
LPS	<20 (Earth)	20	5,200

Table 8. Generation of 1 GWe-Y of Energy

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A1.3 Countermeasures for mitigating the effects of global environment changes

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ABSTRACT

Increased concern over the effects of global climate change and depletion of the ozone layer has resulted in support for the Global Change Research Program. Research to understand Earth system processes is critical, but it falls short of providing ways of mitigating the effects of change. Options and alternatives need to be developed. Space-based concepts for environmental countermeasures should be considered in addition to Earth-based actions. Definition, analysis, demonstration, and preparation of mitigation technology provide a basis for policy response if global change consequences are severe.

RESUME

Les effets des changements climatiques et de l'épuisement de l'ozone font l'objet d'une préoccupation croissante. Ce fait fournit le point de départ pour un Programme de Recherches sur les conséquences des changements atmosphériques. La recherche sur ces conséquences affectant notre planète est d'une importance primordiale mais ne nous donne quand même pas les moyens de les alléger. Plusieurs choix ou alternatives pour minimiser les effets sur l'environnement doivent être développés, dont certains ayant l'espace comme point de lancement en plus de ceux existant sur terre. La définition, l'analyse, la démonstration ainsi que la préparation d'une technologie d'atténuation constitue la base pour une ligne de conduite appropriée au cas où les conséquences s'avéreraient sévères.

Background and Problem Definition

A broad public awareness of the potential for global climate change and for the depletion of the stratospheric ozone layer has been the result of current media attention to issues long troubling the scientific community. These issues have been addressed in the intensive research now under way to monitor, model, and predict the course of environmental change. This activity has been particularly focused in the U.S. Global Change Research Program.[1] The process to establish the rate and magnitude of change will take some time to reach a level of certainty that will support consensus on those mitigating actions which are very costly. By the time a consensus is reached, active response may be imperative.

Policy-making responses can be categorized into prevention, adaptation, and engineering countermeasures.[2] Prevention methods should be used as extensively as economically possible. Adaptation is the ultimate response to change as it has been throughout the history of the world. The primary concern must be the rate of change to be accommodated. As insurance against rapid change, countermeasure options and alternatives for mitigation of the effects of change should be brought to a state of readiness for early implementation.

Both Earth-based and space-based countermeasures should be analyzed to assess benefits, costs, and risks of, implementation. Research and testing of countermeasure concepts should be undertaken to reduce the risks inherent in instituting an intervention program. Formulation of these programs should parallel ongoing research into the environmental processes of the Earth to reduce the reaction time in commencing required countermeasures.

Space-based Mitigation Concepts

The use of space for monitoring the Earth is universally accepted. The Mission to Planet Earth (MPE) Program represents an effective application of the overview of the globe available from an orbiting spacecraft. Instruments can collect data over vast areas in relatively short periods of time. Concepts for space-based environmental countermeasures are not as apparent. The scale of a system concept capable of effectively interacting with factors affecting the global climate or the ozone layer is orders-of-magnitude larger than any current space program.

One of the better defined concepts is the Solar Power Satellite (SPS).[3] The idea of generating enormous quantities of electricity in Earth orbit and beaming the energy to the surface as

an alternative to fossil fuels has fascinated engineers to an increasing degree since Dr. Peter Glaser proposed it.[4] Technical feasibility of the SPS has not been an issue so much as the cost and economics of operation. Particularly in this case, the magnitude of the undertaking must be placed in perspective by the potential benefits of a nonpolluting renewable energy source.[5] The extensive analysis of the SPS addressed in system definition studies[6,7] in the late 1970s resulted in a data base and many individual concept supporters. Renewed interest in the SPS emphasizes the need to examine the assumptions and analysis in the context of benefits to the environment. One interesting aspect is the construction of the SPS using materials from the Moon. This linkage to the Space Exploration Initiative (SEI) has been considered in the context of spin-off benefits from the exploration program.

Variations in the SPS approach to obtaining energy from space should also be investigated. Lunar-based power generation as proposed by Criswell and Waldron[8] provides some advantages over the geosynchronous orbiting SPS. These advantages may be countered by the increased operational complexity and initial investment to develop the system. This system has solar energy conversion devices located on the surface of the Moon. Microwaves are used to transport the energy back to Earth via orbiting reflectors. Lunar materials would be used to make the system economically practical.

Lunar materials figure in an entirely different method of reducing use of fossil fuels in the economy on Earth. Helium-3 is present in significant quantities in lunar soil. It will combine with deuterium in a fusion reaction that is cleaner than the current fusion approach to generate electrical power.[9] The development path for this alternative energy approach will undoubtedly be expensive and risky. Access to mine the helium on the Moon and the focus of fusion research are impediments to fulfilling this alternative energy source. It is conceivable also that an orbiting fusion reactor could impart a breakthrough in fusion technology from the vacuum and microgravity environment of space. The benefits of clean fusion power may be well worth the investment.

The potential for generating large quantities of power in orbit opens the consideration of concepts for dealing with other environmental problems such as depletion of the ozone layer in the stratosphere. Related innovative concepts include the use of radio waves, laser beams, or particle beams to conserve the ozone layer. These emanations might be used to ionize offending chlorine molecules which then would be less active in destroying ozone. Dr. Wong has proposed generating radio waves on the ground to transfer energy to free electrons in the stratosphere to ionize chlorine.[10] By locating the generator in Earth orbit, the energy beam projected tangentially to the troposphere has a longer path in the ozone layer. The technique by Stix[11] of using lasers to remove chlorofluorocarbons from the atmosphere of the Earth may also be more effective from a space-based system. The use of mirrors to increase laser path length also might apply to orbiting reflectors to bounce the space-based laser beam around the Earth.

These and other related innovations should be analyzed for technical feasibility, risks, and benefits. The process should start with an open and objective exposition of a concept. No ideas ought to be rejected without a fair and comprehensive assessment. Robert Goddard said, "It is difficult to say what is impossible, for the dream of yesterday is the hope of today and reality tomorrow."

Regional Working Groups for Initiating Countermeasure Concepts

Meeting problems of global environmental changes will be an international endeavor. Bodansky points out that, "Given a scientific consensus and technical solutions, there may be a hope of developing international agreements to curtail CO_2 emissions."[12] This applies to active countermeasures to a greater degree. To address countermeasure ideas and policy options in their formative stages, alternatives to convening major workshops or conferences are desirable. A network of regional working groups concentrating on space-based countermeasures may be a workable approach. Made up of academia, industry, and government, these multidisciplinary bodies can contribute to the formulation of concepts for mitigating the effects of global change as well as to participation in the initial technical analysis of the concepts. Such working groups can operate with little in direct-funding resources by providing a forum for expression and interchange among scientists and engineers working on related tasks. Daring and farsighted ideas can receive critique and analysis in an open and uninhibited interchange. The early activities of the regional working groups will support higher level committee deliberations. Preliminary definition and technical analysis will provide the basis for formal systems-level engineering studies that are coordinated with other areas of global change research. The product of the group studies would be an experiments and technology development program leading to a capability for action to reduce the effects of environmental change.

Summary

The fundamental task of understanding the Earth system processes is immense. Anthropogenic factors, in an uncontrolled experiment, are inducing modifications to the conditions that evolved to support current life systems. Incontrovertible evidence of the effects of change may not be established until change is far advanced. As Thomas Hardy observed, "The resolution to avoid an evil is seldom framed till the evil is so far advanced as to make avoidance impossible." Preparation for action will be important in avoiding the impact of the predicted evil, anthropogenic-induced change to the global habitat. If global environmental changes are severe in rate and magnitude, the international community will need all of the tools that can be provided to alleviate the effects on society. The principal theme for response is the proper use of technology in combating the consequences of past technological practices on the environment.

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A1.4 Solar Power Satellites: Energy source for the greenhouse century?

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Abstract

Energy is needed to produce wealth, and an increasing world population will need increasing amounts of energy to improve its standard of living. Through the use of a carbon cycle model, it is shown that continued reliance on fossil fuels will cause a global greenhouse warming. An energy-CO_2-economics model is used to project future demand for fossil-fuel-generated energy. When this demand is compared with the fossil fuel use that is permissible if a global warming is to be avoided, a shortfall in energy becomes evident. Terrestrial photovoltaics, nuclear fission, nuclear fusion, and the solar power satellite (SPS) are examined as means of making up this energy shortfall. On comparing these technologies, the SPS appears to be the most feasible means of providing the required energy and preventing a global warming. Laser, 2.45 GHz, and 35 GHz SPS technologies are intercompared, and results indicate that the 2.45 GHz technology remains the most feasible SPS option.

Résumé

L'énergie est indispensable à la production de richesses et un accroissement de la population mondiale en exigera une quantité croissante pour son niveau de vie. Grâce à un modèle de cycle carbone, on démontre que la dépendance continuelle sur les combustibles fossiles sera cause de réchauffement global de serre. Un modèle d'énergie -CO_2- économique est utilisé pour évaluer la demande future d'énergie générée par le combustible fossile. Quand cette demande est comparée avec l'usage de combustible fossile qui est permis si un réchauffement global doit être évité, une crise d'énergie saute aux yeux. Le photovoltaïque terrestre, la fission nucléaire, la fusion nucléaire, et les centrales solaires spatiales (SPS) sont examinés comme des moyens de compenser le manque d'énergie. En comparant ces technologies, le SPS paraît être le moyen le plus réalisable de fournir l'énergie nécessaire qui évite un réchauffement global. Le SPS associé aux canaux laser, 2,4 GHz ou 35 GHz fait l'objet d'une étude comparative, suggérant l'utilisation de 35 GHz.

Introduction

Anthropogenic CO_2 emissions, predominantly from fossil fuel combustion, have increased the CO_2 concentration in the atmosphere from a pre-industrial value of about 270 parts per million (ppm) to about 350 ppm today. Climate models predict that the earth will warm by 1.5 to as much as 4.5 °C due to a doubling of CO_2 in the atmosphere. Possible consequences of a greenhouse effect range from a rise in the sea level, causing flooding of lowlands, to a shift in weather patterns. Many schemes have been suggested to decrease the amount of CO_2 being put into the atmosphere, including injecting the CO_2 emissions into the ocean[1], afforestation, fertilizing the Antarctic waters to increase carbon uptake, and some more esoteric schemes such as preventing the melting of the polar ice caps and changing the earth's surface albedo by injecting aerosols into the atmosphere. Some of these schemes are extremely energy intensive, others are only curative in nature, and some may have disastrous "side-effects" on the climate system. The only reliable path toward preventing a global warming is the reduction of fossil fuel combustion over the next few decades and the next century.

The standard of living (gross national product per capita) that can be developed and maintained in a country is closely tied to the amount of energy per capita it consumes. With most of the population expansion of the world taking place in the third-world, these developing and under-developed nations will attempt to increase their standard of living through the next decade and well into the next century. This will be done mostly by the combustion of fossil fuels, which will add to the emissions and the greenhouse effect. Thus, there are two conflicting needs in the world energy economy: (1) the energy needs of expanding populations seeking a better standard of living, which could create an upward trend in fossil fuel combustion and CO_2 emissions; and (2) the need to limit global warming, which would require a downward trend in fossil fuel combustion and CO_2 emissions. It is first necessary to calculate the shortfall in energy supply that occurs because of these two factors that drive the world energy economy in two different directions, which is the main theme of this paper. This paper goes somewhat beyond this and investigates the choices to make up this shortfall in energy supply. The alternative energies considered here include terrestrial solar photovoltaics, nuclear fission, fusion, and solar power satellites.

The Greenhouse Effect

For approximately the past 200 years, the economic development of the industrialized nations has been fueled by increasing amounts of fossil energy sources. In recent years, there has been increasing concern about the possible environmental effects of the emission of carbon dioxide resulting from fossil fuel combustion. The increasing level of CO_2 emission is well documented and is depicted in Figure 1. The increase of CO_2 emissions has been most drastic during the past 50 years and now stands at approximately 6000 million metric tons of carbon per year[2]. It is likely that unless non-fossil fuel energy sources are developed soon, the rate of emissions will continue to rise. The consequence of this anthropogenic CO_2 emission is an increase in the CO_2 concentration in the atmosphere. All fossil fuel emissions do not directly contribute to an increase in concentration, because there is complex carbon cycling through several so called "reservoirs" in the earth system, namely the atmosphere, the biosphere, the ocean, and the fossil fuel inventory. This "carbon cycle" controls the CO_2 concentration in the atmosphere by processes involving chemical equilibrium between the ocean and the atmosphere. Global climate models

(GCM's) predict that a doubling of atmospheric CO_2 concentration will lead to an increase in global mean temperature between 1.5 and 4.5 °C due to the greenhouse effect.

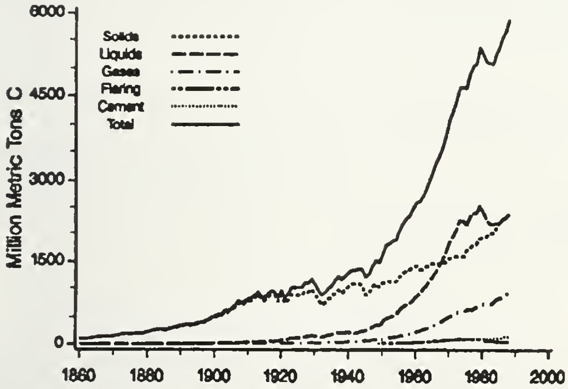

Figure 1 Global CO_2 emissions from fossil fuel burning, cement production, and gas flaring, 1860-1988. (From Reference 2.)

The greenhouse effect can be understood better by examining the radiation budget of the earth. A small fraction of the short wavelength electromagnetic radiation emitted by the sun is either absorbed or reflected to space by the earth's atmosphere. The rest of the short wavelength radiation makes it to the earth and is absorbed and converted to heat. The earth loses heat both by evaporation (the hydrologic cycle) and by radiating the heat as long wavelength infrared radiation. The atmosphere warms due to solar and earth radiation, which it radiates both to space and to the earth. This radiation warms the earth. CO_2 is one of the main gases which traps the heat in the atmosphere. The atmosphere behaves like a greenhouse that traps sufficient heat to enable the growth of plants.

Figure 2 shows global-mean temperature change for the period 1861 to 1989 relative to the average for 1951 to 1980, and is obtained from the assessment of the Intergovermental Panel on Climate Change (IPCC)[3]. This global-mean temperature is a combination of the temperature measured over land and sea and is smoothed. The graph shows that the earth has warmed by about 0.5 °C in the last 130 years. Most of the warming occured between 1910 and 1940 and then after 1975. 1990 was the warmest year ever[4] and the warmest five years before that were in the 1980's. It is uncertain whether the warming of the last century can be attributed to the natural variability or the greenhouse gases. An unambiguous greenhouse warming may not become apparent for several more years. However, our investigations of the effect of continued reliance on fossil fuels show that it is likely to become quite significant during the next century. What would be the consequences of such a warming? Many climatologists have written extensively about the consequences of a global warming and we provide a summary here. One of the primary effects of global warming is expected to be the drying of continental interiors, with significant negative consequences for agriculture. For example, Hansen, et. al.[5], using the Goddard Institute of Space Studies Global Climate Model (GISS GCM), suggest that a doubling of atmospheric CO_2 concentration would cause hot dry conditions in much of the western United States, Canada, and major parts of central Asia. The increased warming could also cause a melting of glacial ice, which may lead to an increase in sea level and lowland flooding in many parts of the world. Many authors have suggested that the western Antarctic ice sheet could collapse, resulting in major sea-level rise.

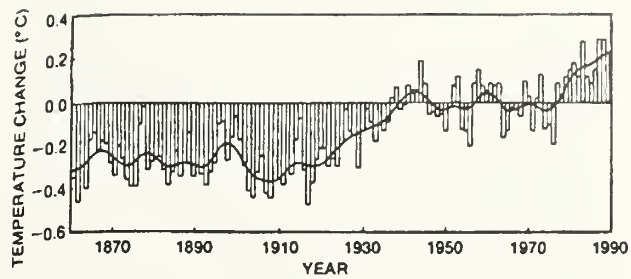

Figure 2 Global-mean combined land-air and sea-surface temperatures, 1861-1989, relative to the average for 1951-80. (From Reference 3.)

Energy and GNP

It has been suggested by numerous authors that there is a correlation between energy consumption and gross national product per capita. This issue was considered by us in some detail and in this paper it is assumed that gross national product is a good indicator of the standard of living. Data for gross national product per capita, population, and energy consumption per capita are from Reference 6. These data sets were aggregated into nine groups of countries in accordance with the groupings developed by Edmonds and Reilly[7]. The following nine groups, comprising the entire world, were used:

1. United States (US)
2. Western Europe and Canada (WEC)
3. Japan, Australia, and New Zealand (JANZ)
4. Eastern Europe and the Soviet Union (EUSSR)
5. Centrally Planned Asia (AC)
6. Middle East (ME)
7. Africa (AFR)
8. Latin America (LA)
9. South and East Asia (SEAS)

The data shows that for both GNP per capita and energy consumption per capita, region 1 had the largest value and region 9 had the smallest value. The disparity in the standard of living and the respective energy consumption is quite large, with a ratio of values for these regions of 39:1 and 59:1 respectively. In order compress the range for plotting, the values for the nine regions were normalized to U.S. = 1, and then the logarithm (to the base 10) was taken. A least squares straight line fit was calculated for these log normalized values (see Figure 3). In doing this fit, data for the nine regions were weighted by their population. Figure 3 shows the log normalized energy consumption per capita versus the log normalized GNP per capita. The data points lie close to the line, demonstrating a correlation between energy consumption per capita and GNP per capita.

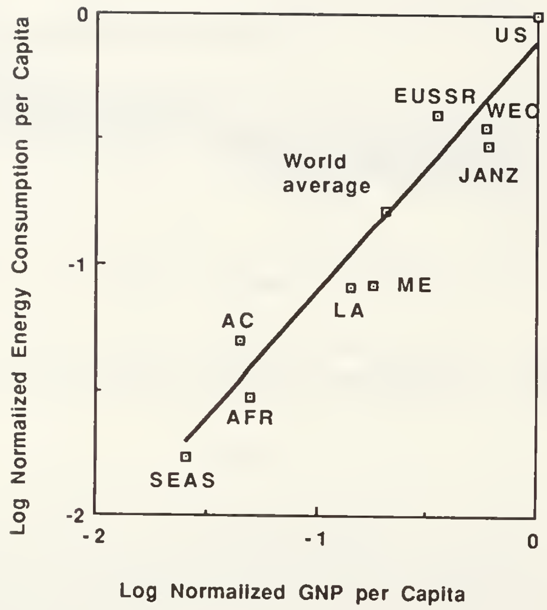

Figure 3 Log normalized energy consumption per capita versus log normalized gross national product (GNP) per capita for aggregates of nations. Abbreviations next to points refer to the regions of the world listed in the text.

Carbon Cycle Modelling

If the world is to satisfy its growing energy needs through fossil-fuel-generated energy, it is necessary to predict the resulting climate change (if any), in order to determine if non-fossil fuel alternatives should be developed, and, if so, to what extent they will have to be deployed. The way we have done this is by determining a limit on the allowable fossil fuel combustion (or emission) that will be permissible when the greenhouse constraint is imposed. A useful tool in this endeavor is a carbon cycle model. Such a model calculates the change in atmospheric CO_2 concentration that results from the emission of CO_2 into the atmosphere (e.g., from fossil fuel combustion). Wigley has devised an elegant carbon cycle model (henceforth referred to as the forward model) that he has inverted[8]. The inverse model calculates the emission of CO_2 that would lead to a given concentration. Since fossil fuel energy production relates directly to emission of CO_2, and atmospheric concentration of CO_2 relates to global warming, these models can be used to relate fossil fuel energy production to global warming. The forward model can thus be used to predict the globally averaged temperature change that would result from a given emissions (or energy) profile. The inverse model can be used to give an emissions (or energy) profile that would cause a given temperature change.

Wigley's work is based on earlier work by Maier-Reimer and Hasselmann[9]. Atmospheric concentration of CO_2 is given by the following convolution integral:

$$C(t) = \int_0^t E(t-u)\, G(u)\, du \qquad (1)$$

where

$C(t)$ = atmospheric CO_2 concentration
$E(t)$ = Rate of CO_2 emissions
$G(t)$ = impulse response (Green's) function
t = time
u = variable of integration.

Maier-Reimer and Hasselmann calculated $G(t)$ for three different pulse injections of CO_2. Wigley's models interpolate between these three impulse functions as the total CO_2 emissions range between the values of the three impulse injections. Total CO_2 emission is given by:

$$E_{TOTAL}(t) = \int_0^t E(u)\, du \qquad (2)$$

In this integral, $t = 0$ refers to the beginning of anthropogenic CO_2 emissions (in the year 1770). The impulse response functions are of the form:

$$G(t) = a_0 + \sum_{j=1}^{4} a_j \exp(-t/\tau_j) \qquad (3)$$

where a_j are numerical coefficients and τ_j are decay times. The fraction of emissions that remains permanently in the atmosphere is given by a_0. Note that Equation 3 represents the form of *each* of the three impulse response functions. Thus, the models use a total of 15 different a's and 12 different τ's. The impulse response function represents the ability of the oceans to take up CO_2 from the atmosphere. Primary electricity was subtracted from the total energy requirement in conventional fuel equivalent to obtain fossil fuel use for the year 1986 (Reference 10). The total CO_2 emissions for 1986 was then considered and the small contribution from cement production was subtracted[11]. The conversion factor from CO_2 emissions to fossil fuel generated energy production was obtained by taking a ratio of the fossil fuel consumption to the CO_2 emissions. The year 1986 was used because it was the most recent year for which data was available. The relationship between atmospheric concentration and global warming was based on an equation from Berner, et. al.,[12] and is given by:

$$C(t) = C(0) \exp(nt/s) \qquad (4)$$

where
$C(t)$ = atmospheric CO_2 concentration t years from today
$C(0)$ = atmospheric CO_2 concentration today
n = rate of temperature change in degrees per year
s = climate sensitivity in degrees Celsius.

Note that here, the climate sensitivity is the temperature change that results from the CO_2 concentration increasing by a factor of e, not 2. In our modelling, the best estimate of 2.5 °C for CO_2 doubling was used[3]. To obtain s for Equation 4, this was divided by ln(2) to give 3.6 °C. For the inverse model, n was specified as an input, CO_2 concentration was calculated from Equation 4, emission was calculated by using the inverse of Equation 1, and then emission was converted to energy. Here, C(0) is the concentration for the year 1990. The results are plotted in Figure 4. For years before the present, the concentration is based on observed data, so that the graph shows implied fossil fuel energy production. For 1991 and beyond, the graph shows the maximum allowable fossil fuel energy production which would limit global warming to the rates indicated. Note that in order to hold the globally averaged temperature to its 1990 value, fossil fuel energy production must immediately be cut by approximately two-thirds, and then must continue to decrease over the next century. This scenario confirms Wigley's emission results for the case in which the future CO_2 concentration is held to its 1990 value. If we allow a 1 °C per century global warming, then fossil fuel energy production must immediately be cut by approximately one-third, but it can then be allowed to slowly increase over the next century. These energy scenarios show a discontinuity at the year 1990 because we are now using fossil fuels at a rate consistent with a global warming greater than 1 °C per century. By comparing the slope of the 2 °C per century curve with the slope of the curve prior to 1990, it is

seen that at current rates of fossil fuel use, a considerable amount of global warming is likely during the next century. Of the three curves in Figure 4, only the 2 °C per century scenario represents an energy scenario that can be achieved without an immediate and drastic energy production decrease. Setting strict limits on global warming thus results in some rather contrived and unrealistic fossil fuel energy production profiles. It would therefore make more sense to set limits on fossil fuel energy production and then examine the effect on climate. This was done using Wigley's forward model, with an input fossil fuel use that varies by a fixed percent per year. To accomplish this, Equation 4 was solved for n; this temperature increase rate was then integrated over time to give a temperature difference from 1990. Thus,

$$n(t) = s \ln[C(t)/C(t-1)] \qquad (5)$$

where
$n(t)$ = temperature increase rate during year t in °C per year
s = climate sensitivity in °C
$C(t)$ = CO_2 concentration at the midpoint of year t
$C(t-1)$ = CO_2 concentration at the midpoint of year t-1.

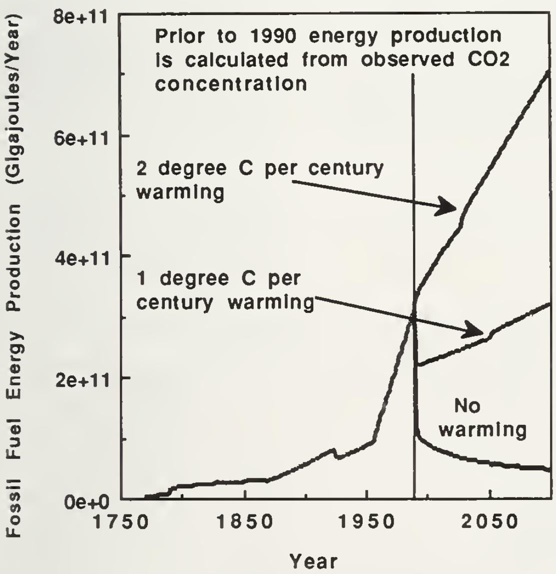

Figure 4 Allowable annual fossil fuel energy production calculated for the three global warming scenarios indicated in the graph. Prior to 1990, energy production is inferred from observed atmospheric CO_2 concentration.

Equation 5 is a result of applying Equation 4 to a single year and then solving for n; thus, the right side of Equation 5 can be thought of as being divided by one year. The units of both sides of Equation 5 are therefore consistent. The temperature difference from 1990 for year t, called $\Delta T(t)$, is given by:

$$\Delta T(t) = \Delta T(t-1) + n(t) \qquad (6)$$

The value of $\Delta T(t)$ has been initialized at 0 for the year 1990. Figure 5 shows $\Delta T(t)$ for 1990-2100 for five fossil fuel use (and thus emission) scenarios. These scenarios include a two percent and one percent increase as well as a two percent and one percent decrease of the fossil fuel emission each year from the 1990 value, and a scenario in which the emission remains constant at the 1990 value. Since we are applying a steady-state temperature model to a transient scenario, our results for temperature increase are somewhat higher than they should be for the larger fossil fuel use increases. For fossil fuel use changes that are small positive, zero, or negative, steady state and transient results are similar. It must be kept in mind, however, that all of our results are somewhat optimistic, since only the effect of CO_2 emission is considered in this model. However, CO_2 is not the only greenhouse gas that results from fossil fuel use. Thus, increases in fossil fuel use should be avoided, as they will result in several degrees of global warming by the year 2100, as seen in Figure 5. If fossil fuel use in the years after 2100 rises at one or two percent annually, then temperature will continue to rise. If fossil fuel use is held constant at 1990 levels, then a little over 1 °C of temperature increase will occur by the year 2100, but the increase will eventually level off. If fossil fuel fuel use decreases, the temperature increase during the 21st century will be fairly small, and temperature will eventually level off to its pre-industrial value. Keeping in mind the somewhat optimistic nature of these models, a 1% annual decrease in fossil fuel use was chosen as a basis for comparison with projections of future world energy needs. This 1% annual decrease can be thought of as a constraint on fossil fuel use that is necessary to avoid a serious alteration of the earth's climate.

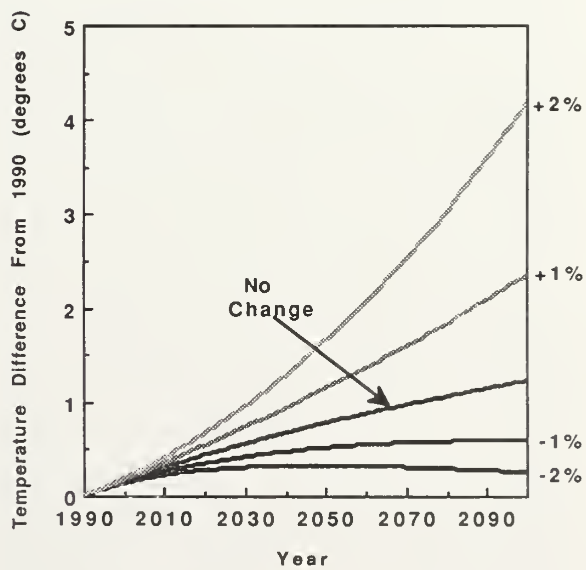

Figure 5 Global mean temperature difference from 1990. The five curves shown are the projected results of the following future changes in fossil fuel energy production: 2% increase per year, 1% increase per year, no change from 1990 value, 1% decrease per year, and 2% decrease per year.

Projection of Future World Energy Demand

In order to compare constraints on fossil fuel energy production with world energy demand, a projection was done

using a computer model. The model used here is the Oak Ridge long term global energy-CO_2 model, developed by Edmonds and Reilly[7] of the Institute for Energy Analysis of Oak Ridge Associated Universities; it provides assessments of the CO_2 emissions due to fossil fuel use, as well as a host of vital information regarding the world economy's many possible scenarios[13].

The computer model divides the world into nine different regions mentioned earlier, based on energy resources and reserves, economic and technical compatibility, social similarities, and geographic proximity. Five benchmark years are chosen for the projections, which start in 1975: 2000, 2025, 2050, 2075, 2100. For each of these periods, the model sets up a balance between total energy demand and energy supply, giving as a result the projected CO_2 emissions. This is done through four interacting modules: Supply, Demand, Balance, Emission. The Supply module works on such data as the price of extraction of the primary fossil fuels: oil, coal, and gas; and the prices of transportation, refining, and production of electricity from the above. These are used to forecast a market price for each of the benchmark years and for each of the regions. In addition, production of energy through terrestrial solar, nuclear, and hydroelectric power is calculated. The Demand module uses such information as population growth and technology improvement parameters to forecast regional and global GNP, and, therefore, the energy demand. If the projected total supply and demand for a particular period do not match, the Balance module perturbs the initial input prices until global balance is obtained. The calculation of carbon emissions, once the production of fossil fuels is known, is carried out by the Emission module through the use of fuel-burning coefficients.

The four modules work on a pre-specified set of data, which are often specified for each of the six forecast periods and for each of the nine areas mentioned above, and that can be changed with the aid of a computer editor. A default set of such data, contained in the model version we have been using, has permitted us to perform a basic run of the program and to obtain valuable information. In particular, we were interested in world energy demand as well as GNP per capita projections. The results are shown in Figures 6 and 7. In Figure 6, energy demand (in gigajoules per year) is plotted versus time (years), starting from 1990. We have plotted the total demand for fossil fuels (oil, gas, and solids), together with the projected total energy demand. The gap between total energy demand (which reaches about 2.5 x 10^{12} gigajoules per year in 2100) and fossil fuel demand corresponds to the use of nuclear, terrestrial solar, and hydroelectric sources. Figure 7 shows GNP per capita, in thousands of 1975 US \$, versus time in years, starting from 2000, for each of the nine regions, together with the world average GNP per capita. The abbreviations on the horizontal axis refer back to the aggregates of countries in the section on Energy and GNP. The numbers on the bar graph refer to per capita GNP values of the appropriate group of nations for the year 2100. Well into the twenty-first century, the Middle East seems to have the largest per capita GNP, while South and East Asia has the lowest value of about US\$ 11,000 per capita; world average (referred to as TOT) is about US\$ 29,000 per capita. The disparity between the wealthiest and poorest groups of nations reduces from a factor of 39 to a factor of 12 between now and the next century.

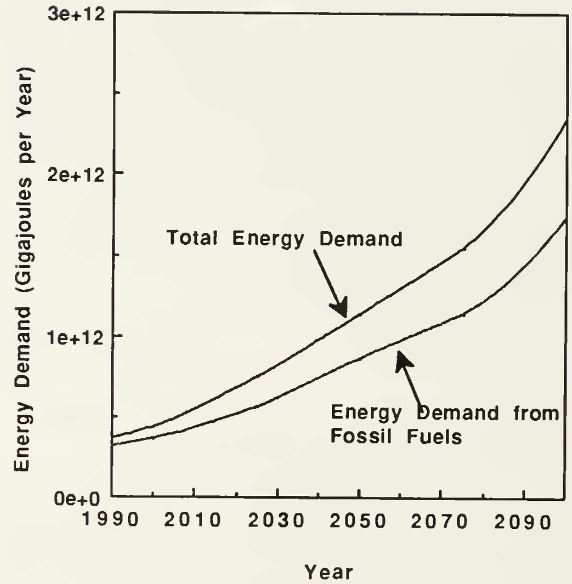

Figure 6 Projected annual world energy demand calculated using the IEA/ORAU model. Both total energy demand and fossil fuel energy demand are shown. The difference between the two curves corresponds to the use of nuclear, hydroelectric and terrestrial solar energy.

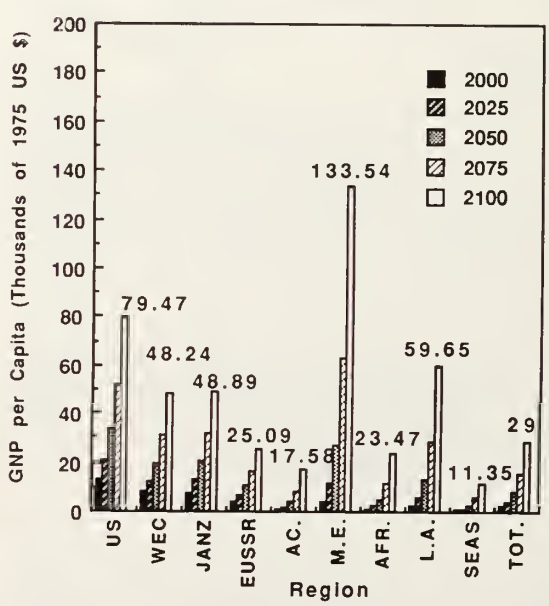

Figure 7 Projected gross national product (GNP) per capita for five benchmark years for the nine regions of the world listed in the text. Projected world average GNP per capita is also shown.

Constraints on World Energy

At this point in time, world energy is constrained by three factors, namely the environment, the resources, and demographics and economics together. While energy policy should be formulated within the constraints imposed by these factors, more often than not, in most countries energy policy has been dictated by market forces. The fact that fossil fuel resources are limited and that alternative energy development should be a priority was recognized in the brief interlude following the oil shock of the 1970's. With the advent of the mid 80's came the era of a glut of cheap oil and the alternatives were tossed away. One may probably even speculate that some potentially major conflagrations could have been avoided if reliance on Middle East oil was done away with in the last three decades. Numerous studies have examined the world energy problem from the viewpoint of the finite resources of both fossil and nuclear energy, and we only wish to state that it is a key issue, but is beyond the scope of this paper.

In the earlier sections of this paper, we have tried to investigate two of the three constraints, namely the environmental and economic. The economic argument is closely linked to the demographics issue. The population of the world is expected to increase significantly during the 21st century. Most of this increase will occur in the developing nations. Currently, some of these nations lag behind the developed nations by more than an order of magnitude in both per capita energy consumption and per capita GNP. In order to improve the standard of living of the developing nations and provide for an increasing population, world energy production will have to increase greatly. If this energy is produced by fossil fuel combustion, the atmospheric concentration of CO_2 will increase, leading to global warming due to the greenhouse effect.

In the previous sections, it was pointed out that in order to avoid greenhouse warming, a one percent per year reduction of CO_2 emissions will have to be put in place almost immediately. This reduction in CO_2 emissions translates into a cap on the amount of fossil fuel combustion permissible, and this is shown in Figure 8 (the curve is labelled allowable fossil fuel use). Also shown in Figure 8 is the total fossil fuel demand that would be necessary to fuel the economy of the world. When these two curves are compared, a shortfall in energy becomes apparent and this shortfall will have to be made up for with the use of non-fossil fuel energy sources.

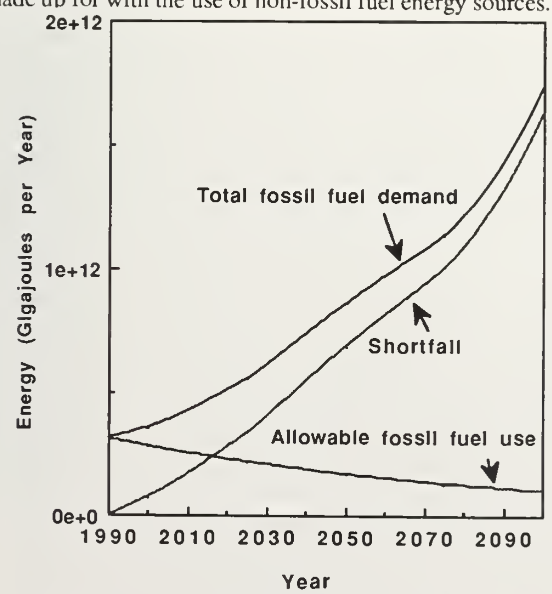

Figure 8 Projected world energy shortfall determined by subtracting allowable fossil fuel energy production (based on a 1% annual decrease in fossil fuel energy production starting in 1990) from the projected annual fossil fuel energy demand. The allowable production was determined by the need to prevent the global greenhouse warming.

Non-Fossil Energy Alternatives

The alternative energy sources to fossil fuel combustion considered in this study are terrestrial solar photovoltaics (PV), nuclear fission, nuclear fusion, and solar power satellites (SPS). Solar energy available at the earth's surface, when averaged over the day/night cycle, the seasons, the different latitudes, the 50% average cloud cover of the earth, and even some attenuation in clear air, is perhaps one-tenth of that available in space. Great progress in conversion efficiency and costs of solar cell modules has been made in recent years. The highest efficiency achieved by a non-concentrating experimental cell was 30%[14], while 10 to 12% efficiency for large operational modules seems to be typical. Cost of electricity generated by photovoltaics stands at 30 cents per kWh, about a factor of five more than the cost of power generated by conventional utilities. The major problem of terrestrial PV is not the installed cost of the solar cell modules but storage cost and the intermittent nature of solar insolation. The storage battery that is most preferable for terrestrial photovoltaics is a lead-acid battery designed for deep discharge[15], and at this point is the best technology available. Costs of the lead-acid battery are almost 400 times the average price of the solar cells per kWh. Furthermore, the best of these are limited to about 1500 charge-discharge cycles. Consequently, battery lifetime is less than the lifetime of the PV modules themselves requiring that they (the batteries) be replaced approximately every four years. Since these batteries are expensive to begin with, it is likely that energy storage is the economic bottleneck for terrestrial solar energy. Hubbard[16] points out that a major problem with PV is the fluctuations in the power output due to sudden changes in the cloud cover. Furthermore, during overcast sky conditions and the night, there would be no power produced, and these problems, Hubbard feels, might lead to problems in the interfacing of PV with the electrical grids.

Nuclear fission power has the advantage of being a well-developed technology that is already being used. However, a great deal of controversy remains as to the safety of nuclear power plants. Waste disposal as well as security concerns about the production and shipping of ever-increasing amounts of fissionable material are also issues that remain to be solved. Most of the fissile material that is used in conventional nuclear reactors is an oxide of ^{235}U. The abundance of ^{235}U in natural uranium is about 0.7 % and the rest is mainly ^{238}U. Thus it is apparent that with a limited supply, conventional reactors (henceforth referred to as burners) cannot be utilized to make up the shortfall of energy and hence, breeder reactors will have to be used if nuclear energy is to become the alternative to fossil fuels. Breeders convert the ^{238}U to ^{239}Pu (plutonium) which then undergoes fission to produce energy. A term commonly used by designers of breeders is the concept of doubling time. Waltar and Reynolds[17] define reactor doubling time as "the time required for a particular breeder reactor to produce enough fissile material in excess of its own fissile inventory to fuel an additional reactor", and this time is on the order of 15 to 20 years. Thus, a breeder program akin to the French would already have to be in place if breeder reactors are going to make up the energy shortfall in the future. This is because most countries are exploiting their uranium resources in burners, and by the time breeders would be deployed, sufficient amount of ^{235}U would not be available to breed the ^{238}U.

Nuclear fusion power has several advantages over fission. There is no danger of melt-downs, radioactive wastes are short-lived, and the deuterium or tritium fuel can be extracted from sea water. Furth[18] reports that the ratio of fusion output power to heating input power (called Q) must be about 30 for an economical power reactor, and that the power levels of fusion experiments have become inconveniently high as Q has increased. Figure 9 shows the output power of fusion experiments versus the input power, where Q is approximately 1 in recent experiments. A commercial reactor would have an output of perhaps a gigawatt, which Furth predicts will come on line around 2020 and will be the largest engineering endeavor ever undertaken. Nuclear fusion thus

will have to be a large-scale operation, and may be many years away from being feasible. After almost 40 years of research worldwide, with huge research budgets (for example, the U.S alone spends about $400 million each year), scientific and technical breakthroughs will have to be made before fusion power becomes a reality.

In light of the above discussion, it appears that the most promising alternative that could make up the energy shortfall in the decades to come is solar power satellite (SPS). The SPS is a satellite in geostationary orbit (GEO), 35,800 kilometers above the equator, which collects solar energy on arrays of photovoltaic panels and beams the energy to earth using either microwaves or lasers. The energy is received on the earth and is routed to users by electric power lines. The advantages of the SPS are that it uses proven technologies, and does not produce greenhouse gases or nuclear waste.

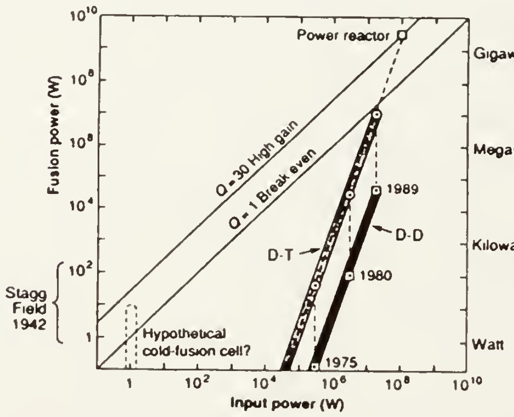

Figure 9 Progress of fusion experiments using the deuterium-deuterium (D-D) and deuterium-tritium (D-T) reactions. The ratio (Q) of fusion output power to heating input power must be about 30 for an economical power reactor. The Q-value of magnetic fusion experiments has been advancing steadily, but the associated power levels have become inconveniently high. (From Reference 18.)

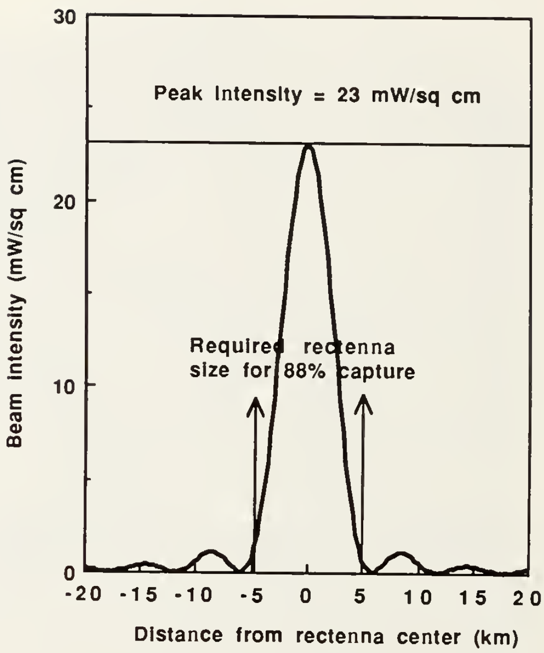

Figure 10 Intensity of a 2.45 GHz microwave beam at an earth-based rectenna. The arrows indicate the size of a rectenna needed to capture 88% of the transmitted power.

Solar Power Satellite Technology Options

Three SPS technologies are compared, which differ in their means of generation and transmission of power. These designs include a 2.45 GHz system similar to the NASA-DOE SPS reference design, a 35 GHz system, and a laser system. The mass of the reference design is about 50,000 metric tons for a 5 GW power level (see for example Reference 19). Recent studies conducted at NASA's Langley Research Center have compared mass estimates for advanced laser power generation and beaming systems[20]. On the basis of their comparison, we conclude that a laser SPS would be several times the mass of an SPS that would use microwaves. Thus we do not examine the laser option, though it might be pointed out that recent successes in concentrators might be able to reduce the mass involved[21].

The Space Studies Institute's study[19] investigated the feasibility of construction of the SPS using lunar materials. The reference design uses transmission through the atmosphere's microwave window at a wavelength of approximately 12 cm. (2.45 GHz). The diffraction pattern for a 2.45 GHz beam was calculated assuming a quadratic aperture, and is shown in Figure 10. A rectenna large enough to capture 88% of the energy would have dimensions of approximately 9.7 x 9.7 km. An exclusion boundary set at a distance where the microwave intensity tapers off to 0.1 mW/cm^2 would be a distance of approximately 6.5 km from the central maximum (assuming that the SPS delivers 6 gigawatts of power to the surface of the earth). A question might be raised as to the value of this calculation, as extremely detailed calculations, designs, and simulations were done during the NASA-DOE SPS program. However, this calculation was done as a benchmark to compare it with the 35 GHz case.

At a frequency of the 35 GHz atmospheric window, for a given amount of power transmitted, the amount of land needed would appear to be less as compared to the 2.45 GHz case. This would make building rectennas near populated areas (where the power is to be used, but where less land is available) more feasible. Using the same 6 GW transmitted as in the case of 2.45 GHz, the diffraction pattern was calculated for reception at the equator, and is shown in Figure 11. Note that the width of the 88% capture area has decreased to 0.7 km (i.e., by a factor of 2.45/35), so that only about 1/200th as much land is apparently needed. However, due to the increased height of the secondary diffraction maxima, the 0.1 mW/cm^2 exclusion zone would be a distance of about 3.3 kilometers from the center. Thus, the savings in land is not as large as anticipated, though it might be possible that using an optimized gain taper might reduce the land area in the 35 GHz case. Furthermore, the assumption that the same 6 GW can be concentrated into a smaller land area may be environmentally unsound, since the peak microwave intensity would increase from 23 mW/cm^2 (for 2.45 GHz) to 4600 mW/cm^2. If the size of the SPS were scaled down so that the peak intensity of the 35 GHz beam was 23 mW/cm^2, then the power leaving the transmitter would have to be restricted to about 32 MW, because of which more SPS units would be needed to make up the shortfall, so that there would be no savings in land area. However, if the demonstration of SPS technology is the goal that is set forth, 35 GHz technology might be considered as an additional option, since the units would be smaller and might more easily be financed and constructed. However, microwave lenses in space have been suggested as a means of increasing the effective aperture of the SPS transmitting

antenna[19]. This would allow for smaller rectennas, while retaining the 2.45 GHz frequency.

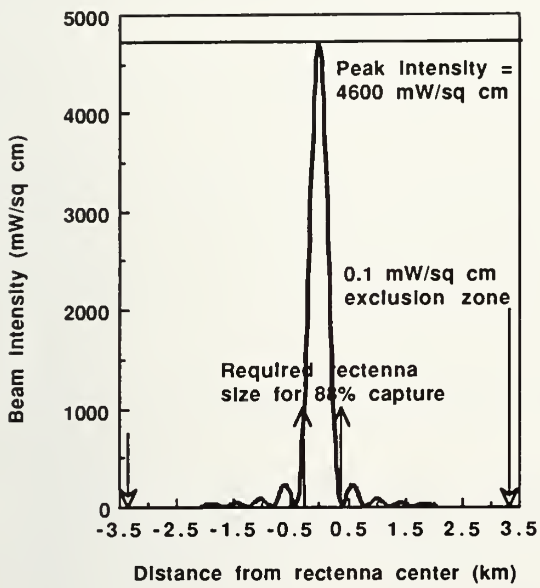

Figure 11 Intensity of a 35 GHz microwave beam at an earth-based rectenna. The arrows indicate the size of a rectenna needed to capture 88% of the transmitted power, as well as the size of an exclusion zone based on safety considerations.

The long-term feasibility of 35 GHz power transmission is limited by rain, cloud, and atmospheric attenuation . For a typical temperate zone rainfall rate of 5 mm/hour, the transmission efficiency is only 17% (our calculation was based on Ref. 22, page 39, Figure 29). Similarly, atmospheric attenuation at 35 GHz is approximately 90 TO 95% (our calculation was based on Ref. 22, page 39, Figure 28a). The overall power link efficiency will be lower at 35 GHz at this point in time as both DC-to-RF and RF-to-DC conversion efficiencies are lower than at 2.45 GHz. With time, 35 GHz technology will probably approach 2.45 GHz efficiencies, but the attenuation problem cannot be done away with. Thus, either the total SPS generating capacity would have to be increased, and a ground based energy storage system developed, or additional rectennas would have to be constructed. The latter proposal would involve building more than one rectenna for each SPS unit, so that the beam can be redirected on rainy days. This would involve additional land area, added complexity in the SPS units themselves, as well as additional transmission losses along the ground as power is transmitted from a rectenna located where rain is not falling to users located where rain is falling. Thus, further development of 35 GHz power transmission does not appear to be desirable for SPS, although it may have space-to-space or earth-to-space applications and other potential applications.

The NASA-DOE SPS study was terminated in 1980, with the National Research Council estimating that the cost of an individual SPS would be very large. Since then, several important studies on the feasibility of constructing an SPS using lunar materials have been conducted by the Space Studies Institute[19]. In addition, SSI has also conducted several experiments on mass-drivers, telerobotic assembly, manufacturing lightweight composites from lunar composite materials, and is in the process of designing a lunar-probe to investigate the availability of water on the moon. In addition, the strides made in solar cell efficiencies and concentrators can reduce the mass of the solar panels on an SPS by 50% and the overall mass by 20%. Power beaming technology today is much more mature than it was ten years ago. Carbon fiber composites developed for the space programs might further reduce the mass of the SPS. As SSI has demonstrated, the transportation costs to LEO can almost be eliminated if the SPS is built of lunar materials. In the short-term, CO_2 emission reduction treaties should be signed. Such treaties should be linked to the adoption of alternative energy sources by the signatories to displace their fossil fuel consumption. The world can either continue to pump CO_2 into the atmosphere and wait and watch the globe warm or can cooperatively pool its resources together to secure a peaceful and prosperous future for its citizens. As we have demonstrated, the time to act, is now!

Conclusions

While the economy of the world can become somewhat less energy-intensive through conservation, the increase in the world's population, especially in developing nations, will necessitate extensive increases in energy production in the coming years. Climatological studies show that if this done through continued reliance on fossil fuel combustion, a global greenhouse warming of several degrees is likely to result by the end of the 21st century. Therefore, new energy sources must be developed. Those considered in this paper include terrestrial photovoltaics, nuclear fission, nuclear fusion, and the solar power satellite (SPS). Of these technologies, only the SPS produces no nuclear waste, requires no technological breakthroughs, and does not rely on costly energy storage techniques. Development of SPS should begin immediately through international cooperation to prevent a global warming, and the efforts should be concentrated on 2.45 GHz as the frequency at which power is beamed to the earth.

Acknowledgements

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A1.5 Energy in Asean: an outlook into the 21st century

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ABSTRACT

This paper presents the story on energy in ASEAN: energy resources, energy demand versus elasticity, how to cope with the energy demand, and an outlook into 21st century. The energy problem of the next century does not only arise from a physical scarcity of resources, but also from the technical, economic and environmental problems associated with some sources and the difficulties involved in the introduction of major new technologies.

RESUME

Cet article expose l'énergie en ASEAN : les ressources énergétiques, la demande d'électricité et son élasticité, comment faire face à la demande d'énergie et une prospective pour le 21ème siècle. Le problème énergétique du siècle prochain n'est pas tant lié à la pénurie des ressources, qu'aux problèmes techniques, économiques et environnementaux associés à l'utilisation de certaines sources énergétiques sans oublier les difficultés liées à l'introduction de nouvelles technologies de production de masse.

INTRODUCTION

The Association of Southeast Asian Nations (ASEAN) was formed in Bangkok in 1967 by five countries : Indonesia, Malaysia, the Philippines, Singapore and Thailand. A sixth nation, recently independent Brunei Darussalam, joined the association in 1984. These six countries are situated along the equator in Southeast Asia. While Thailand and Peninsular Malaysia are located on the southeastern tip of mainland Asia, the other countries are archipelagoes. These countries cover a total land area of approximately 3.1 million square kilometres with a total population of 303 millions in 1987.

The region is as diverse in the geographical distribution of population and resources as its gross domestic product (GDP) per capita, which varies from $ 15.422 in Brunei Darussalam to $ 590 in Philippines (Table 1). Energy consumption per capita is highest in Singapore (4.46 toe) which is nearly twenty times that of Indonesia (0.230 toe).

Table 1: GDP per capita and Energy Consumption in ASEAN Region, 1987

Countries	Population (millions)	Area ('000 km^2)	GDP per capita (85 US $)	Energy Consumption per capita (toe)*
Brunei	0.2	6	15 422(1)	3.80
Indonesia	172.0	1.919	646	0.23
Malaysia	16.5	330	2 562	0.78
Philippines	57.4	300	590	0.38
Singapore	2.6	1	7 074	4.46
Thailand	53.6	542	1 025	0.33

Sources: mainly from "Energy Indicators of Developing Member Countries of ADB", (*) World Development Report 1990 and IEA; (1) 1985.

The region's proved fossil fuel reserves are given on Table 2. In 1990, proved oil reserves were estimated at 13.3 billion bbl, gas reserves 146.6 trillion cubic meters and coal reserves

7 billion tonnes of bituminous coal and almost 20 billion tonnes of lignite. The reserves, respectively, for oil and gas would last around 20 and 50 years; for coal the reserve would last more than 100 years.

Table 2: Proven Fossil Reserves ASEAN Region, 1 January 1990

	Estimated proved reserves		
	Oil (billion of bbls)	Gas (trillion Cu.meters)	Coal (billion tonnes)
Brunei	1.000	7.000	
Indonesia	11.000	76.000	A 0.014 B 5.200 L 18.000
Malaysia	3.100	52.000	B 300 L 120
Philippines	0.020	22.000	B 1.500
Thailand	0.080	9.600	L 1.500
Total Asean	13.203	146.600	A 0.014 B 7.000 L 19.500

A: Anthracite B: Bituminous L: Lignite

Sources: mainly from "Energy Indicators of Developing Member Countries of ADB" and from the conference "Megatrends the Asia-Pacific Energy Outlook Toward 2000", Oct 1990, Jakarta.

This paper presents the story on energy in ASEAN : energy resources, energy demand versus elasticity, how to cope with the energy demand, and an outlook into the 21st century.

ENERGY RESOURCES

The ASEAN region is rich in hydrocarbon resources. Brunei, Indonesia and Malaysia have made the region the world's leader in LNG trade as natural gas is more evenly distributed in the region than oil reserves. In 1987, ASEAN produced 2.1 billion b/d of oil and 8.0 Bcfd of natural gas. This is equivalent to 36% of oil and 61% of gas produced in the Asia-Pacific region whose total daily oil production is about 11% of the world's production. Singapore is the only ASEAN member country without hydrocarbon resources. Her strategic position in the oil and gas trade routes for the Asian-Pacific region has turned her into the world's third largest refining centre including the storage, transport and distribution of petroleum products. This position however, is rapidly changing as Indonesia and Malaysia have stepped up their refining capacities and due to the intense competiton from the Middle-East as well. Brunei, Indonesia and Malaysia are major oil and gas exporters in ASEAN, with Thailand, Philippines and Singapore heavily dependent on imports.

The ASEAN coal reserves are estimated at about 27 billion tonnes, comprising 75 per cent lignite and brown coal, about 20 per cent sub-bituminous coal and 5 per cent bituminous coal. Assuming an average calorific value of 4500 kcal/kg the coal reserves represent about 12 billion mtoe. The bulk of these reserves are located in Indonesia. The ASEAN region also has vast peat deposits, estimated at about ten times the total coal deposits.

The development of indigenous energy resources is a common policy to all ASEAN countries since the 1972 oil price shocks. This is reflected in the intensified efforts on oil, coal and gas exploration and development.

Table 3: Hydropower and Geothermal Resources

Country	Hydropower	Geothermal
Indonesia	75.000 MW or 400 TWH	10.000 MW 70 TWH
Malaysia	25.000 MW or 90 TWH	-
Philippines	10.000 MW or 40 TWH	6.000 MW
Thailand	9.000 MW	

The renewable energy resources of this region are also large (Table 3). The total hydropower potential is estimated at 119 GW, capable of an annual energy generation of about 500 Twh. However the harnessing of these potentials has been impeded by an incompatible geographical distribution between hydropower resources and load centres. Most of these resources are in Irian Jaya and Kalimantan where electricity consumption is presently insignificant. ASEAN is also one of the world's largest geothermal areas. Although the geographical distribution is more favourable compared with that of hydropower, the geothermal installed capacity is still small because the capital cost of developing the resources is relatively high.

ENERGY DEMAND

Analysis of Energy Demand and Elasticity

A principal concern of this analysis is the extent to which countries have adjusted to perturbations in the energy environment. A prerequisite for analysis of that question is a model of what form the behaviour of countries might have been in the absence of the perturbation.

The simplest model of any merit which relates energy use to total economic output involves a single income elasticity. On a national basis this would be written:

$$E = KG^{\alpha}$$

or in terms of per capita

$$(E/N) = k(G/N)^{\beta}$$

where E is commercial energy consumption, G is gross national product (GNP) and N is population; K,k α and β are constants ; α, β are the income elasticities of consumption. If this model held, then plots of the relevant parameters describing energy use and income would give straight lines on a log scale. The trajectories on a per capita basis are shown in Figure 1. It is clear that this simple model does have great explanatory power despite being unfashionable. The country trajectories lie within a rather narrow corridor.

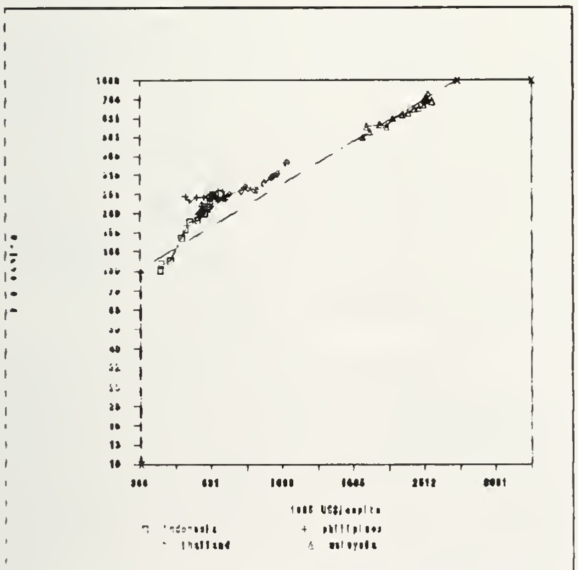


Figure 1 Commercial Energy Consumption against GDP per capita

One way of estimating the change in behaviour since the first oil shock is to take cross-country behaviour as a measure of the "norm" elasticity and to determine how individual country elasticities measured from their own time series compare with the norm. This approach assumes that cross-country elasticity measures the relationship between energy and output as it built up over the long historical period in which the country differentiations were established, whereas time series elasticities measure post oil shock behaviour. If there have been significant behavioral shifts from the historical norm then the time series elasticities will be different from the cross-country elasticity. If economic development were simply a progression along a determined path which was followed at different speeds by different countries then the cross-country and time series elasticities should be roughly similar. If countries have now moved on to a more energy conservative track than the historical track characterizing the separation between countries, then time series elasticities should be below cross-sectional elasticities.

The income elasticities for energy demand of each country estimated from their time series are presented in Table 4 for the periods 1973-85, 1973-8 and 1978-85. A few values are not well estimated, for reasons which will be explained later, but most are adequate. The estimated elasticities vary widely from the average cross-country elasticity of 1.13, in Asia, but not in any systematic fashion. Thailand is significantly lower over the whole period. Singapore, Malaysia, and Indonesia are significantly higher. There is no general tendency for elasticities to be higher or lower in the earlier or later period, although in almost all countries they vary significantly between the 1973-78 and 1978-85 periods.

Table 4: Income elasticities of per capita energy consumption in ASEAN Countries

	1973-85	1973-78	1978-85
	Estimated value	Estimated value	Estimated value
Philippines	0.24	0.51	1.16
Singapore[a]	1.47	2.55	0.86
Thailand	0.76	0.84	0.79
Malaysia	1.31	1.23	1.45
Indonesia	2.04	2.50	1.46

a: Elasticities are for 1971-82, 1971-78 & 1978-82
Source: Energy Policies in Asia, Nigel Lucas, 1988.

Malaysia and Indonesia have time series elasticities significantly above the norm for 1973-85. This is presumably because the high income from oil production was spent at the margin on energy intensive activities. Singapore also has a higher value than the norm, presumably because energy use in the oil refinery industry increased with throughput and a shift to upgrading processes.

In summary, the simple income elasticity model is better from a cross-country than from a time series point of view. National time series do not fit an income elasticity model well and their deviations from the model show no systematic trend. The extent to which country elasticities differ from cross-country elasticity does not correlate

with income level ; so there is no evidence of a tendency for the countries as a group to have been on a lower energy path recently than the one implied by the historical development which has produced the present cross-country differentiation.

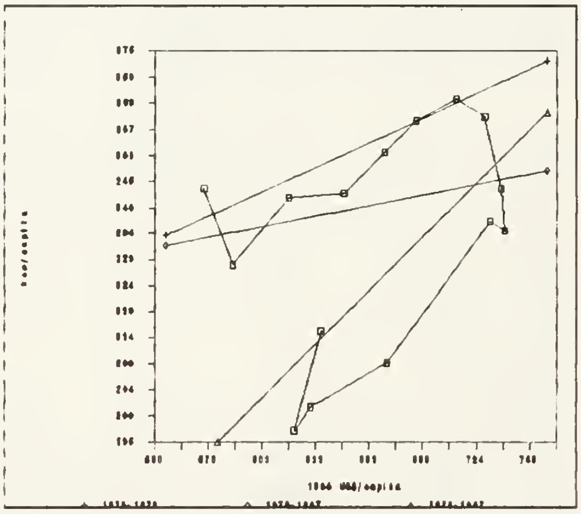


Figure 2 : Per capita energy consumption and GDP for Philippines

One should caution that any attempt to compare the behaviour of different countries require the use of common models which may not in some instances be appropriate. One example is the Philippines, for which the regression analysis summarized in Table 3 is anomalous. The reason for this is clear when the data are plotted as in Figure 2. Occasional inappropriateness of this sort do not undermine the analysis provided they are recognized and the right adjustments made.

<u>Electricity Demand and Elasticity</u>

A similar elasticity analysis may be made for electricity demand. The log-log plots are shown in Figures 3 and 4, not only for ASEAN countries which are developing countries with low income, but also for the developed countries with high income such as Japan and France and some countries with intermediary income such as Spain and Greece.Again there is strong linearity among the trajectories. The pattern is linear past a certain income threshold.

On figure 3, one can see that the gradient of the regression for the ASEAN countries, specially for Indonesia, is higher than that of developed countries as Japan and French. It means that the present technology allows a rapid energy development for the developing countries.

Figure 4 reveals remarkable consistency between Malaysia, the Philippines and Thailand. The trajectories of the three countries lie closely along a single straight line. The gradients of these trajectories of generation against output is the income elasticity of demand for electricity. The gradients are the same and approximately constant over the period; the trajectories are coincident. In addition, these trajectories are almost parallel with that of Greece.

The trajectory for Indonesia is markedly different. It begins from a lower base, because Indonesia was under-electrified compared to other ASEAN countries, but has a higher gradient implying that the country will "catch up" and join the same trajectory as the other countries in the region. On these figures, two developed countries (Japan and France) with high incomes and two intermediary countries (Spain and Greece) are included. However, all trajectories lie in a narrow corridor, as can be seen on figure (4), which show the trajectories on a per capita basis.

A regression analysis of the pooled data for Malaysia, the Philippines and Thailand gives an estimated income elasticity of 1.65. This elasticity confirms the visual impression of a high level of conformity of the data to a simple exponential model. If Indonesia is included and a regression made for ASEAN as a single economic entity then the income elasticity for ASEAN would be about 1.98. The same regression applied to the developed countries gives an income elasticity of about 1.

In ASEAN countries, any improvement is not expected to change this elasticity significantly due to growing industrialization and increasing income. Moreover energy intensity in the industrialized countries tends to decrease while in the developing countries it is still the same or increasing.

If the trend of elasticity were extrapolated to 2010 then at a 6% growth rate in GDP, giving nearly 12% growth in electricity demand, the gross electricity generation in ASEAN would be about 1400 TwH. This represents an increase of 14 times the generation in 1987. This simple extrapolation is only to set the scene and emphasize the remarkable potential for growth which exists within ASEAN. Energy wise, in the year 2010 the share of ASEAN in the world would be bigger than it is today.

In the period to the end of this year, a project "ASEAN 2010" implemented by the ASEAN-EC Energy Management Training and Research Centre (AEEMTRC) should supply better energy forecasts in order to enhance the existing basis for long term energy cooperation in the region and to foster commitment to ASEAN cooperative programmes and projects.

Figure 3 : Gross Electricity Generation against GDP

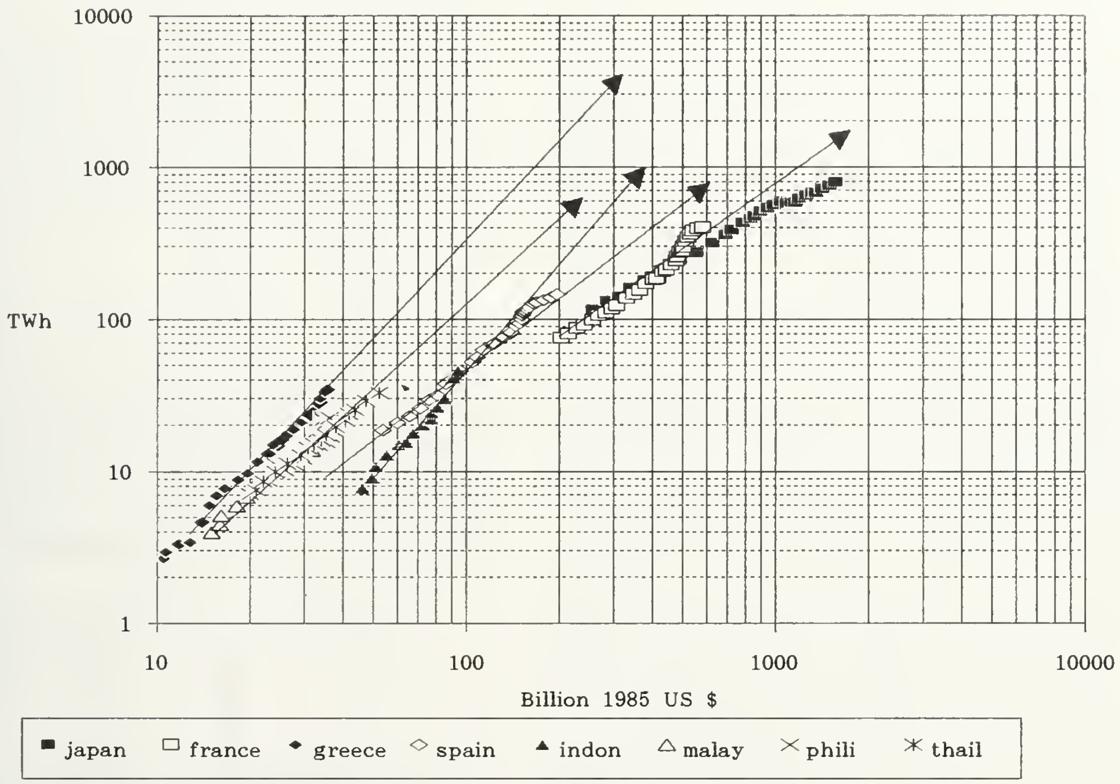
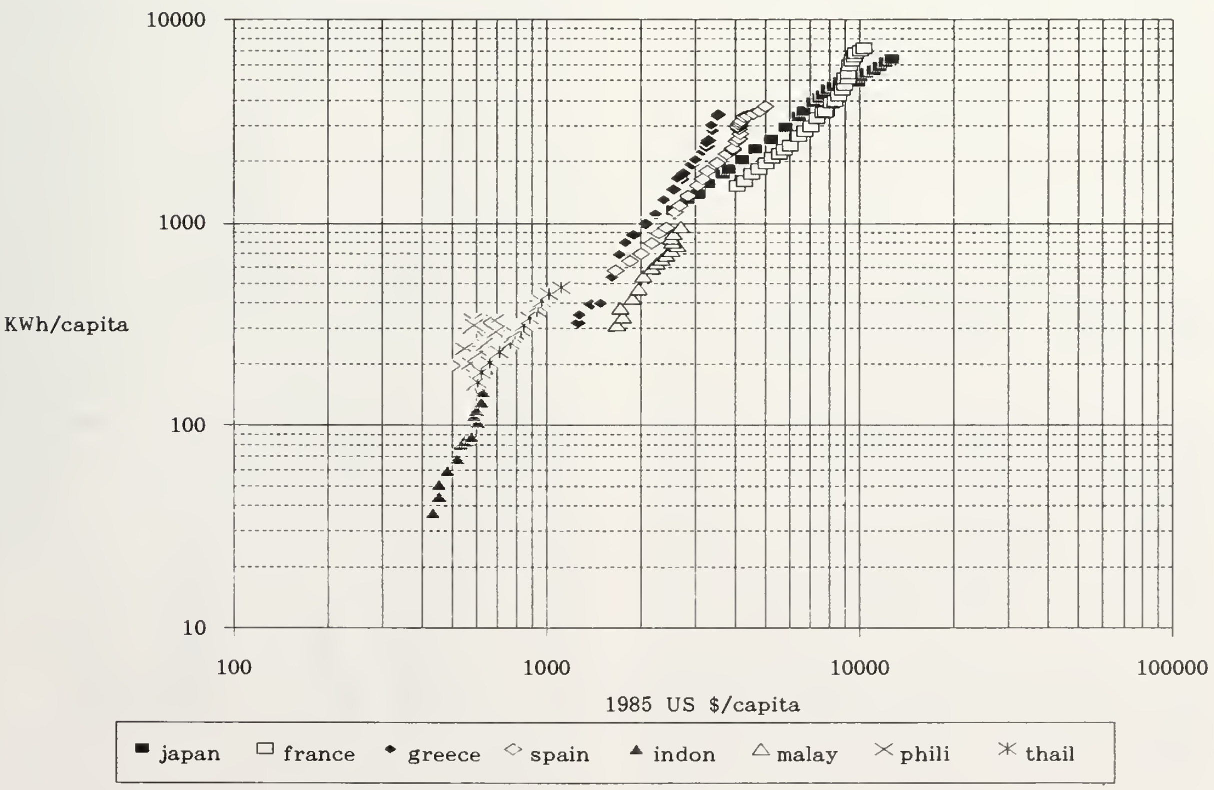


Figure 4 : Gross Electricity Generation against GDP per capita



HOW TO COPE WITH THE ENERGY DEMAND

Capital Scarcity

Evidence has so far been adduced for an electricity sector growing faster than GDP. It would be normal in such circumstances to suppose that the capital investment required to support a continued expansion at this rate would also grow faster than GDP and therefore would take an increasing share of GDP. If this were so, then it would be serious because electricity generation is capital intensive, and the burden would be heavy.

In ASEAN, the present level of electrification is lower than that of industrialized countries. Therefore the share of fuel used for electricity generation in the region is much lower than that in industrialized countries, although it would increase dramatically in the coming decades. Recent growth rates in installed electric power capacity, as well as in the planned or estimated installation for the rest of this century are shown in Table 5 below. Obviously these rates exceed economic growth rates.

Table 5 : Average annual growth in installed electric power capacity

Country	Historic 1979 - 89	Planned / Estimated 1989 - 2000
Indonesia	13.8%	7.7%
Malaysia	12.6%	7.2%
Philippines	4.5%	6.6%
Thailand	11.3%	9.1%

Source: DR. V.KRISHNASWAMY, Profile of growth in electrification in ASEAN, August 1990.

The reasons for the slower rates of growth of installed capacity during the rest of the decade are the rapid past capacity expansion and financial bottlenecks to expanding such capital intensive investments at higher rates. In addition, rehabilitation of existing systems, including the improvement of the efficiency of distribution networks, is beginning to receive more attention than in the past, when the focus was more on system expansion. Success in rehabilitation and efficiency improvements would reduce the need to expand capacity in some cases or lessen the problem of power shortage in others.

Use of Energy Resources within ASEAN

In spite of the earlier practice of not linking indigenous energy availability and economic performance at the national level, new electricity generating capacity was increasingly relying on indigenous resources (natural gas, coal and hydro). Recent events in the Gulf have reinforced this trend. The uncertainty about future oil supplies and prices makes indigenous non-oil resources a more secure choice.

For ASEAN countries, the share of electricity generation utilizing coal will be more significant. One can see on the figures (5.1- 5.2- 5.3- 5.4) the coal share increases strongly to more than 40% in 2000 for Thailand and to 20% for the Philippines; it more than doubles compared with 20% in 1987 to almost 50% in 2000 for Indonesia.

Figure 5.1 : Electric Generating Capacity by Fuel Type for Indonesia

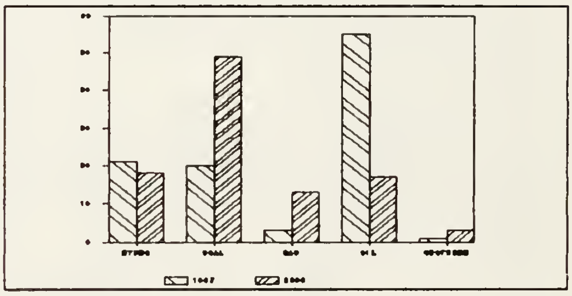


Figure 5.2 : Electric Generating Capacity by Fuel Type for Malaysia

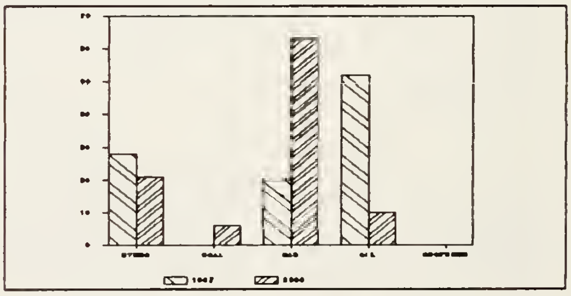
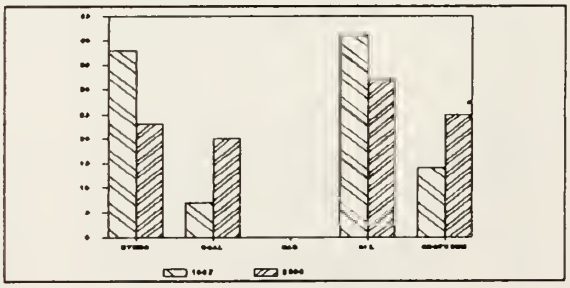


Figure 5.3 : Electric Generating Capacity by Fuel Type for Philippines



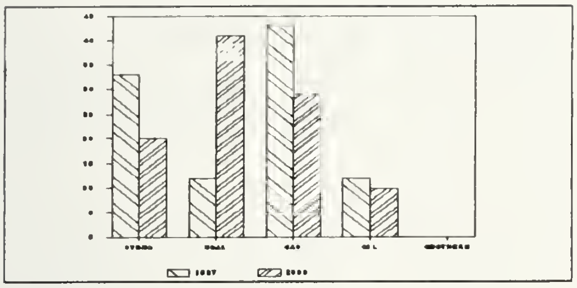


Figure 5.4 : Electric Generating Capacity by Fuel Type for Thailand

On the other hand, the share of oil in electricity generation declines in all ASEAN countries. At the end the shares of natural gas increase especially in Indonesia and Malaysia. In Malaysia, gas has replaced oil, significantly, acquiring a share above 60%.

SPECIFIC CONSTRAINTS FOR ENERGY DEVELOPMENT

For the end of this century, a capacity addition of around 45 GW is being planned. The sheer size of the expansion programme may call for organizational or institutional innovations. It is not always possible to increase the unit sizes and reduce the number of units. Water constraints in hydro, steam constraints in geothermal, natural gas and good quality coal constraints, as well as the inherently fragmented nature of the systems (such as those in Philippines and Indonesia) may compel the utilities to construct generating units of small sizes with correspondingly heavy organizational burdens. Environmental considerations may have the effect of delays, making projects much more expensive than originally planned, and even of cancelling many of the hydro, coal-fired and geothermal power projects.

The power sector already draws some 10 - 20% of the government budget. Innovations to be adopted to mitigate or overcome these problems will include creation of a larger number of utilities, greater participation of the private sector through build-operate-transfer (BOT), build-own-operate (BOO), and build-own-lease (BOL) options, resort to large turnkey contracts and the use of contracts for operation and maintenance. The construction of combined cycle units is likely to reduce capital costs of base load and intermediate load plants.

Sustainable development requires the simultaneous fulfilment of several goals, some of which are likely to be competing. One such goal is poverty alleviation through economic growth and redistribution of income and wealth. Economic growth and income redistribution are, however, likely to increase the demand for goods and services requiring more use of fossil fuels for consumption and production activities. Using up nonrenewable energy resources may well be in conflict with the sustainability dimension of enhancing the resource base so that the future potential to meet human needs and aspirations can be expanded. What is required is a strategy for technology-oriented investments that broadens this scope so that the transition to an environmentally acceptable backstop energy technology set becomes smooth. This implies a balance between investments, innovation and consumption that allows for continued growth. Furthermore the rapid increase in the use of fossil fuels may be in conflict with the fundamental environmental dimensions of sustainable development.

LONG-TERM ENERGY DEVELOPMENT

The ASEAN region can, therefore, go a long way toward diversifying its energy sources away from its dependence on oil, if concerted efforts are exerted to utilize to the fullest all energy resources available in the region. But one has to be realistic enough to accept that the region's available energy resources cannot make it completely self-sufficient in the next century. In this context, ASEAN countries may have to find other alternatives :

- to consider or reconsider seriously the need to apply nuclear power in the not-too-distant future; this year Indonesia expects to start with a feasibility and siting study for its future nuclear programme;

- to develop and utilize other new and renewable sources of energy (NRSE) such as biomass, and solar energy; today, NRSEs are far from fulfilling the dreams of the 1970's and appear to have only a marginal role to play between now and 2020. Power from space (SPS), which is the topic of this symposium, is a new energy source which presents a new possibility to solve the problem of scarcity of energy resources and the problem of carbon dioxide in the atmosphere as well.

Until now, the non-existence of nuclear energy in ASEAN countries as in many other developing countries is due to economical reasons, i.e. because nuclear energy remains to be more expensive compared to other energy technologies than in developed countries because of its high-technology content.

Therefore, ASEAN countries need technology transfer to modernize their economies and compete in the world market. ASEAN cannot afford to emulate the developed countries and build up its technical capabilities over a century or more. To catch up all kinds of transfer would be required. But the essential ingredient in any transfer of technology is time.

In the case of SPS, ASEAN would like to profit by the time elapsed to reach the next century, during which the new technologies associated with SPS e.g. microwave energy transmission, high efficiency multispectral photovoltaic structures, space applications, giant structures in space, high-temperature solar receivers etc ... would be developed. Subsequently, ASEAN would be ready to apply this new energy technology through international cooperation involving the developed and the developing countries.

CONCLUSION

In this age of science and technology, industrial development in ASEAN countries is inevitable. In the near future the role of traditional sources of energy will have either declined or will be too limited to power industrial growth. The days of cheap and unlimited fossil fuel energy sources are also over. As the prices of oil rise with galloping speed, most of the developing countries will be forced to search for alternative sources of reasonable, environmentally sound, and reliable energy. Several alternatives need to be explored, such as bioenergy, terrestrial solar energy, and animal energy. However, none of these sources can provide the gigantic energy needs of such a vast population racing for modernization. Hence, an exploration of the new technologies, including SPS, is a must.

So far many analyses point to favourable prospects. Even though the costs of these new energy technologies seem unreasonably high at this stage, international efforts to design an operational system leading to further developments can reduce the cost and offer a viable source of increasing energy supply. Many environmental and financial questions remain to be resolved, but systematic cooperative studies could lead to scientific information of intrinsic value, which can be diffused extensively to the general public. There is great task ahead for bringing new technologies to the developing countries.

One of the central questions for the long term is the transition to renewable energy resources. At present, the prospects are somewhat disappointing in terms both quantity and competitiveness. Their share of the world energy balance would increase 1 to 3 percent by 2020, reaching barely 20 percent of total energy. If hydropower and non-commercial energy are excluded, it would seem that the so-called "new and renewable sources of energy" rise from just 0.3 percent in 1985 to no more than 2 to 3 percent in 2020. Their share, therefore, would emerge very slowly, at least in terms of volume for the main supply systems. On the other hand, they may be of crucial importance to isolated rural communities for use in communication, water-pumping and electricity, even if the human, social or food elements are not significant in terms of energy balances generally.

The Space Power Satellite (SPS) will remain a capital intensive project with the same problems of financing as nuclear power projects today. Although nuclear energy is presently used to an appreciable degree for electricity generation in the developed countries, its role remains insignifant in the developing countries. The reasons for this is because nuclear technology has been acquired in the developed countries and then transferred with additional cost to the developing countries which were not prepared to receive it. By analogy, the question is " How will the developing countries such as ASEAN countries be involved in the development of SPS technology despite the scarcity of their financial resources ? ".

More broadly, research and development efforts are needed to arrive at solutions for the very long term. Though there may be scepticism about their competitiveness, new energy alternatives besides coal will be needed to cope with future demand. For the transition from an energy system based on non-renewable stocks to one of renewable flows, one shall have to look to solar power from space as a reasonable alternative. The recent Gulf crisis which was caused by Iraq's invasion of Kuwait on 2 August 1990 has again taught the developing countries a lesson to pursue that path of transition persistently. Otherwise, they will be further impoverished from oil price increases due to the crisis. According to a United Nations report, with prices of US $ 30 or US $ 40 a barrel, developing nations that import oil would have to pay between US $ 45 billion and US $ 60 billion next year, against US $ 30 billion in 1989. For many of these countries, this will be an unbearable additional burden.

* * *

A2.1 Energy development and environment: What about solar energy in a long term perspective?

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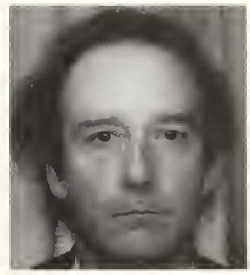

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ABSTRACT

After decades of strong growth, the next century might be that in which the world population is stabilized around 11 billion inhabitants. The development hoped for by the Third World, the probable consequencies of the increase of the greenhouse effect due to man induced emissions, the risks generated by a possible dissemination of nuclear energy to all the regions of the globe, these are among the main questions regarding the next century.

In order to shed some light on these questions, we propose an energy scenario, established from an analysis of the demographic and energy needs evolution, renewable and fossil reserves, environmental issues, technological possibilities and regional imbalances. This scenario shows that solar energy could contribute significantly in the long term energy mix.

We discuss the respective advantages and drawbacks of the different solar technologies: solar power satelites, ground solar power plants and decentralized applications, in relation to considerations linked to the nature of the needs to be satisfied.

RESUME

Après les décennies actuelles de croissance forte, le siècle prochain pourrait être celui de la stabilisation de la population mondiale autour de 11 milliards d'habitants. Le développement espéré du Tiers Monde, les conséquences probables de l'augmentation de l'effet de serre dû aux émissions d'origine anthropique, les risques engendrés par une éventuelle dissémination de l'énergie nucléaire à l'ensemble des régions du globe, autant de questions pour le siècle prochain.
Pour tenter d'apporter un éclairage sur ces questions on propose un scénario énergétique établi à partir d'une analyse de l'évoluton démographique, des réserves fossiles et renouvelables, des contraintes d'environnement, des possibilités technologiques et des déséquilibres régionaux.
Ce scénario montre que l'énergie solaire peut contribuer significativement à la satisfaction des besoins énergétiques, tant par des applications décentralisées que par des installations centralisées: centrales solaires au sol et centrales spatiales. On discute les avantages respectifs de ces différentes filières électriques solaires en fonction de considérations liées à la nature des besoins à satisfaire et des conditions socioéconomiques régionales.

Introduction

The dawning of the 1990s is just the right time for millenarian stirring. The depletion of natural resources, the spread of pollution over the earth's surface, the rising of sea levels, the swallowing up of new atlantides, and the climatic revolution each occupy a prime position among these concerns.

The development hoped for by the Third World, whose runaway increase in population will continue for a long time to come, the energy risks which may be generated by the possible dissemination of nuclear energy to every region of the globe, the probable consequences of the increase in the greenhouse effect due to man-produced gas emissions, all of the above lead us to raise three questions regarding the next century:

- At this future time, might we not find ourselves faced with an energy shortage?

- In order to avoid a possible energy shortage, might we not go from Charybde to Scylla by adopting modes of energy production that are dangerous for both nature and humanity?

- Does not the development of new countries threaten to throw the planet completely off-balance, from both an energy and ecological point of view?

It might be considered completely unrealistic to try to shed light on these formidable questions. Our inability to correctly predict the economic situation ten years from now, and the unforeseeableness of scientific and technical discoveries, provide support for such a criticism.

Nevertheless, the prospective stems from another mode of thought. The aim of providing descriptions of diversified long term scenarios is not to designate the boundaries of a predictable future or to specify the degree of certainty that we can apply with respect to this future. Rather, its goal is to emphasize the imbalances and main points of rupture.

Among them the population stabilisation around 11 billion inhabitants in 2100 appears as one of the principal assumptions.

Technological progress

Without going into an in-depth[1] discussion of potential technological evolutions in the field of energy supply or that of its ultimate use in the 21st century, we would like to stress the following few points:

- The endless potentialities for improvement in energy efficiency in already industrialized countries, but also, and perhaps especially in southern countries currently undergoing development. The history of industrialized countries, and also more recently that of certain countries undergoing rapid industrialization, shows that productivity increase and energy consumption reduction, far from being opposed to one another, as is sometimes thought, are two elements in a single system of improvement [2]. The penetration of technological progress in the southern countries will have even greater consequences due to the rapid growth-rate of these countries.

- The diversification of energy production in two directions: first, by the simultaneous production of several energy carriers (electricity and heat for example), then by the diversification of the nature and quality of main supply sources utilized in obtaining a given amount of energy. This includes the generation of electricity from wood, waste-materials, sun, wind, and the manufacturing of fuel from biomass, coal, natural gas, electricity...Within this context of diversification, renewable energy sources (sun, hydraulic, wind, biomass) have a great potential.

- The appearance of new energy vectors, hydrogen produced from electricity (nuclear, solar or hydraulic) and substitution fuels produced from biomass. In both cases, it is first of all a matter of providing new solutions to the problem posed by transportation, whose importance is greatly increasing world-wide, and which still remains linked to oil. One of the major technological challenge of the 21st century resides in the biotechnological transformation of lignocellulose, and hence, in the direct transformation of wood into motor fuels.

Finally, three domains of research, which are still experimental, need technological breakthroughs to reach a major quantitative impact before 2100. These include:

- Controlled thermonuclear fusion, whose demonstration of feasibility gets pushed back further and further each year.

- Large solar satellites (several tenths of km^2), placed in geostationary orbit, which transmit electric energy to the earth by microwaves.

- Geothermy of hot dry rocks, obtained in creating a heat exchanger at a depth compatible with the desired temperature and artificially fed with water.

Last we do not consider that neither effective technique for eliminating carbon dioxide produced by fossil-fuel resources, so as to make possible the relaunching of a massive development of coal supplies, nor development of new approaches which would not lead to any cumulation of highly active long-life nuclear waste will emerge significantly before 2100.

The NOE scenario

"New Options for Energy"[3].

Among the different scenarios that we have studied, there is one, the NOE scenario which strives to mitigate simultaneously two main environmental threats of the future, that is the cumulation of CO_2 in the atmosphere and of nuclear waste on earth. There is no reason indeed, in the present state of our knowledge, to give preference to one of these two threats:

- Either we let the greenhouse effect take place in order to avoid the use of nuclear energy, by wagering that we will find solutions for eliminating CO_2, or that we will adapt ourselves to the probable climatic disruptions.

- Or we let long-life nuclear waste accumulate at a parabolic rhythm in order to avoid the greenhouse effect, by wagering that we will find solutions for the permanent decontamination of these waste, or that future generations will adapt themselves.

The NOE scenario is the result of an approach which takes a global and regional view on the matter. This approach, based on the advice of experts, does not require an analytic heavy modelization (Medea type)[4]. The approach is global in that it looks at evaluations of primary energy consumption and does not explicitly analyze final consumption per type of use. It is regional because it relies on a splitting up of the world into ten large regions, 4 for the North, 6 for the South, regrouping countries with close characteristics. This splitting up is a result of the analysis of the world energy situation as it is presented in the World Energy Atlas [5].

The constraining hypotheses are set forth in physical terms. This is preferable to economic growth-rate and price of oil type econometric hypotheses, which seem to us to be less pertinent in the long term.

The set of constraining assumptions retained pertain to:

- The regional demographic evolutions, until 2100, according to UN estimations [6], which appear as the main factor of demand (table 1);

Table I: Evolution of the world population

POPULATION (in millions)	1960	1985	2020	2060	2100
North America	200	265	330	380	400
Europe	360	430	450	450	450
Japan Australia N Zealand	125	170	230	240	250
USSR Central Europe	310	390	490	530	550
All of the Northern countries	995	1255	1500	1600	1650
Latin America	215	410	710	1100	1250
North Africa Middle East	145	230	580	800	900
Africa	195	390	1140	1700	2000
India	420	760	1310	1700	1800
China	660	1040	1360	1600	1600
Asia Oceania	390	760	1400	1700	1800
All of the Southern countries	2025	3590	6500	8600	9350
World Total (UN source)	3020	4845	8000	10200	11000

- The estimation of fossil-fuel and renewable resources; this estimation is based on the World Energy Conference publications[7] and completed for renewable energy resources by our previously cited analyses [8].

- The strong connection between the energy system and the environment which induces external constraints on the structure of world energy supplies.

The NOE scenario assumes a willful sustained effort towards energy **conservation and diversification of energy resources**. In particular, stress is placed on the use of **renewable energy resources**, in substitution for fossil-fuel resources.

Environmental constraints lead to the following decisions:

- The return, at the latest by 2100, of fossil fuels induced CO_2 emissions levels lower or equal to the biosphere's maximal capacity of absorption. We took as an annual limit, for emissions at the end of the cycle, the value of **three gigatons of carbon**[9]. This is a temporary value thought by many scientists as the limit beyond which oceans are no longer capable of reabsorbing the excess of CO_2 in the form of carbonate.

- The halt of all nuclear fission energy production, **at the latest by 2100**. In fact, this constraint involves the halt of all construction of new reactors after the year 2070.

These two constraints obviously weigh very heavily on the final evaluation. The limited utilization of fossil-fuel resources, and the renunciation of recourse to nuclear resources in the long-term, make it necessary to emphasize the efforts made towards energy conservation and renewable energy resources.

The first phase of the explorative approach therefore consists in estimating the evolution of the demand for energy in each of the ten regions retained.

J. Goldemberg, T. Johansson, A. Reddy and R. Williams have shown[10] how technological evolution and the spread of effective energy measures could make it possible to reduce the consumption level per inhabitant in the northern countries by half. Their analysis also shows how the southern countries can bring about a sustainable development which would give access to satisfactory living conditions, without their energy needs surpassing their equipment and financial capacities.

We will retain the results of this study, while, nevertheless, pushing back the 2020 deadline set by its authors, taking into account structural, institutional and cultural inertia, as well as economic and financial constraints. We shifted to the middle

of next century an average reduction of one-half for the consumption level per inhabitant in industrialized countries (2.4 toe/inhab/year) and an average rise to 1 toe/inhab/year in the southern countries.

The average consumption values, per inhabitant, are then broken up, taking into account the specific characteristics of the ten regions considered. The total demand in primary energy per region is then deduced by taking account of the growth of populations.

Table II: Energy supplies 2020 2060 2100

ENERGY SUPPLIES 2020 SCENARIO NOE Mtoe	COAL	OIL	GAS	NUCL	HYDR	BIOMAS WASTE	GEOTH	SOLAR WIND	TOTAL	CONS/ INHAB
North America	250	500	410	120	160	80	10	20	1550	4,7
Europe	173	370	250	160	120	65	2	10	1150	2,5
Japan Australia N Zaal	144	220	110	70	30	10	6	10	600	2,6
USSR Cantral Europa	433	300	600	60	140	55	2	10	1600	3,3
All of the N countries	1000	1390	1370	410	450	210	20	50	4900	3,3
Latin Americe	35	265	100	5	185	350	10	50	1000	1,4
N Africe Middle Eaat	5	310	245	0	5	5	0	80	650	1,1
Africe	10	80	30	0	80	250	0	50	500	0,4
Indie	180	120	125	10	30	85	0	20	570	0,4
China	700	195	100	5	150	130	0	40	1320	1
Asia Ocaenia	170	240	230	20	100	330	10	60	1160	0,9
All of the S countrias	1100	1210	830	40	550	1150	20	300	5200	0,8
World Total	2100	2600	2200	450	1000	1360	40	350	10100	1,3
ENERGY SUPPLIES 2060 SCENARIO NOE Mtoe	COAL	OIL	GAS	NUCL	HYDR ›	BIOMAS WASTE	GEOTH	SOLAR WIND	TOTAL	CONS/ INHAB
North Americe	100	200	140	70	200	110	20	60	900	2,5
Europe	80	110	85	90	160	120	5	50	700	1,5
Japan Australie N Zeal	75	70	45	50	40	40	20	60	400	1,6
USSR Centrel Europe	245	110	230	20	250	180	5	60	1100	2,1
All of the N countries	500	490	500	230	650	450	50	230	3100	1,9
Letin America	40	150	100	0	340	550	20	200	1400	1,3
N Africa Middle East	10	310	300	0	10	30	0	390	1050	1,3
Africa	20	100	105	0	190	480	5	200	1100	0,6
India	300	195	350	5	100	150	0	100	1200	0,7
China	570	205	300	5	320	250	5	145	1800	1,2
Asle Oceania	360	250	345	10	190	490	20	185	1850	1,1
All of the S countriee	1300	1210	1500	20	1150	1950	50	1220	8400	1
World Total	1800	1700	2000	250	1800	2400	100	1450	11500	1,1
ENERGY SUPPLIES 2100 SCENARIO NOE Mtep	COAL	OIL	GAS	NUCL	HYDR	BIOMAS WASTE	GEOTH N TECH	SOLAR WIND	TOTAL	CONS/ INHAB
North Americe	40	40	40	0	210	200	30+40	100	700	1,7
Europa	40	40	30	0	200	170	10+40	70	600	1,3
Jepen Austrelie N Zeel	60	30	20	0	50	50	30+30	80	350	1,4
USSR Central Europe	60	40	60	0	340	280	30+40	100	950	1,7
All of the N countries	200	150	150	0	800	700	250	350	2000	1,6
Letin Americe	40	50	50	0	450	600	40+20	250	1500	1,2
N Africe Middla Eaat	10	150	200	0	10	80	0+0	650	1100	1,2
Africe	20	70	80	0	270	600	10+0	500	1550	0,8
Indie	300	270	300	0	150	300	0+30	150	1500	0,9
China	570	150	200	0	400	300	10+20	200	1850	1,1
Asia Oceanie	360	160	220	0	220	620	40+30	250	1900	1,1
All of the S countriea	1300	850	1050	0	1500	2500	200	2000	9400	1
World Total	1500	1000	1200	0	2300	3200	450	2350	12000	1,1

In the second phase of this exploratory approach, we try to build a structure of supplies meeting the demand as it is defined. The iteration proceeds in three steps:

- Estimation of fossil-fuel energy supplies using observed trends, account taken of a self-reduction in fossil-fuel energy consumption in industrialized countries which would occur, first, out of fear of the greenhouse effect (regulations and taxes), then because of the progressive depletion of crude oil and gas resources.

- Sustained mobilization of renewable energy resources, first depending on their regional potential, with a dynamics which takes account of the values observed in the past, then with a partial energy exploitation of uninhabited regions (solar energy in the Sahara, hydraulics in the Himalayas, wind energy in Greenland);

- The balance of energy requirements is met by nuclear power, while assuring the feasibility of the resulting dynamics and a progressive reduction to zero after 2020.

With these hypotheses and this strategy, world energy supplies are established as indicated in table II.

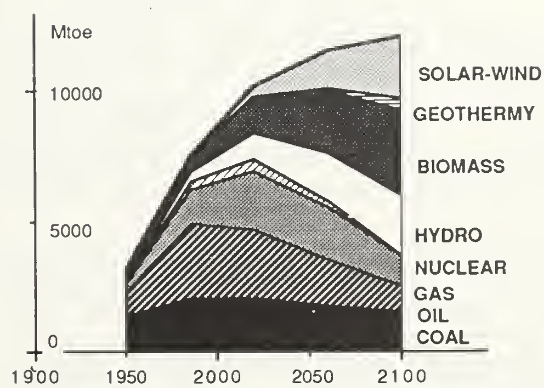
There we can see the following main elements:

- For the northern countries, the very large effort towards energy conservation (4800 Mtoe), the very rapid fall in the recourse to fossil-fuel energy resources, which would be reserved as much as possible in the southern countries, a moderate growth (30%) of nuclear energy until 2020 before its continuous fall until 2100. For renewable energies, an increase of the contribution of biomass to supplies, especially in the form of fuel, sometimes imported from other production zones, the progressive use of the very important hydraulic reserves in the USSR and the rise in solar and wind energy, which would reach significant values after 2060.

- For the southern countries, a major initial increase in the recourse to fossil-fuel energy resources, followed by the beginning of a decrease in 2050 and stabilization at approximately 3000 Mtep in 2100, a nuclear energy supply which remains confined to a few countries in which it is already present before phasing out, an international effort made towards equipping the numerous hydraulic sites in Latin America, Asia and Africa. Nevertheless, it is biomass and solar energy that would play, in the long-term, the major role in these countries reaching nearly half of the final supply.

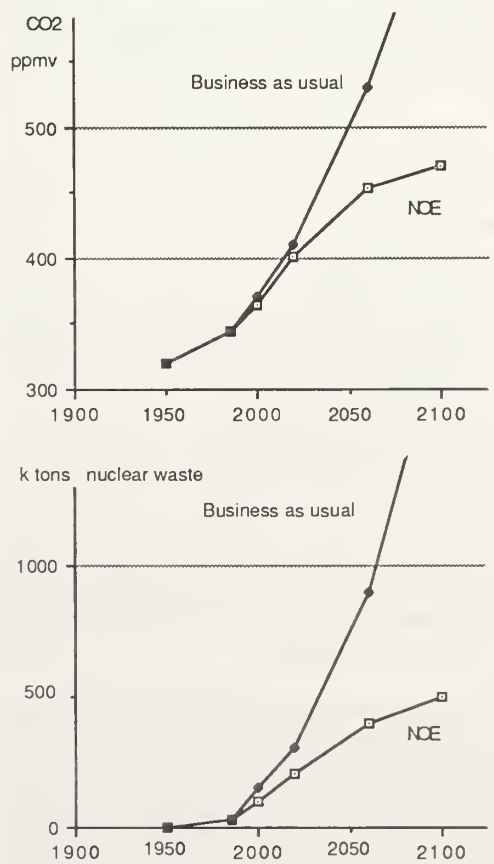
Figure 1 illustrates the evolution of the world energy supplies.

Fig. 1: Evolution of the world energy supplies



The NOE scenario's impact on the environment appears in figure 2. The concentration of carbon dioxide in the atmosphere would be stabilized around 470 ppmv, without reaching the level at which it would be doubled. The stock of nuclear waste would reach a ceiling at 0.5 million tons before the end of the century.

Fig. 2: CO_2 and nuclear waste cumulation



A place in the sun?

The above scenario shows the absolute necessity of an important participation of solar energy to the global energy supply, since 2350 Mtoe are required in 2100. Then the questions are:

- What is the most suitable mix of solar technologies for different regions and various needs at that horizon?

- Is there any room for Solar Power Satelites (SPS) in that mix of solar technologies?

The present technologies are first able to ensure decentralized energy needs for thermal and electrical applications (water and house heating, electrical domestic applications, communications, water pumping and so on). This corresponds to a great number of end-use points, each consuming a little bit of energy, but whose cumulation becomes significant.

On the other hand solar thermodynamic power plants have been successfully demonstrated as producing electricity on the grid. In California, nine solar power plants of the cylindro parabolic mirror type from 30 MW to 80 MW installed in the Mojave desert, supply their electricity to the grid. The competitivity is obtained due to good correlation between electrical needs and sunshine in these regions. A 25% contribution of natural gas is provided to optimise production.

Typical solar characteristics of up-to-date equipment are[11]:

Peak power = 80 MW
Land occupation = 1.6 km2
Reflective area = 0.5 km2
Solar annual production = 180 GWh
Annual equivalent operating time at nominal solar output = 2000 - 2500 hours
Net peak efficiency = 23%
Annual global solar net efficiency = 14%
(for californian insolation characteristics, with 2700 kWh/m2/year of direct irradiation).

Alternative thermodynamic technologies, namely parabolic dishes and central receivers, have been succesfully experienced but have not yet given rise to commercial developments.

Another way is to produce photovoltaic electicity on the grid. Photovoltaic power plants of 1 to 5 MW have been succesfully demonstrated in California and smaller ones (a few hundred of kW) in Japan, Europe and Middle East. Very simple to operate, these entirely automatic plants will certainly have huge developments next century: no pollution, no noise, a minimum maintenance. As they do not need direct sun they tolerate diffuse insolation conditions. The energy cost is still too high today, but the progress outlooks are very encouraging.

Up-to-date typical equipment characteristics are:

Peak power = 5MW
Land occupation = 0.1 km^2
Photocell field size = 0.05 km^2
Solar annual production = 10 GWh
Annual equivalent peak power operating time = 1500 - 2000 hours
Net peak efficiency = 12%
Annual global efficiency = 10%
(for californian insolation characteristics, with 2200 kWh/m2/year of global horizontal irradiation).

Future terrestrial technologies include new generations of solar power plants and eventually biochemical technologies to produce hydrogen directly from the sun.

In that context, SPS technology could reinforce this solar pattern and avoid the difficulties due to climate and night and day alternation, if environment drawbacks are not yet too important. The main environmental concerns associated with SPS are microwave exposure to workers in space and the public; potential radiation effects on space workers; electromagnetic compatibility with space-related sciences like optical and radio astronomy; and electromagnetic emission and chemical effluent effects on radio propagation in the upper atmosphere.

Typical characteristics of a future equipment are:

Peak power = 5 GW
Land occupation = 120 - 170 km2 in the NASA reference case, depending on latitude
Space photovoltaic field = 50 km2
Solar annual production = 40 TWh
Annual equivalent nominal power operation time= 8000 hours.

This type of installation requires obviously huge and rather concentrated electricity needs in the foreseen region as well as sufficient room to set up the reception antenna.

Table III shows a comparison of these different technologies from the point of view of land occupation, peak power and annual energy characteristics.

We would like to emphasize the following points:

Table III: Comparaison of solar technologies

TECHNOLOGY	SPS *	THERMO	PHOTOVOLTAIC	PHOTOVOLTAIC
		DYNAMICS **	POWER PLANT*	REMOTE*
UNIT AREA	100-150 km2	1,6 km2	1,2 -2,5 km2***	1 m2
POWER	5 GW	80 MW	100 MW	100W
kW peak/m2 of land	30-50	50	40 -80	100
OPERATING				
TIME (HOURS)	8000	1800-2000	1500-2000	1500-2000
kWh/m2 of land	240-400	100 -110	60 -160	150 -220
* PV EFFICIENCY = 12% , 10% INCLUDING STORAGE AND POWER CONDITIONNING				
**3 TO 3,5 m2 / MIRROR m2				
*** DEPENDING IF HORIZONTAL OR ORIENTED PANNELS ARE USED,(1,2 TO 2,5 m2 / m2)				

- First, that SPS and terrestrial solar power plants have similar nominal power per square meter of land occupation (SPS 40W/m2, solar power plants 40 to 80 W/m2). Domestic photocells are 2 to 2.5 times better.

- Second, that, concerning annual energy, SPS is 2 to 6 times better than terrestrial power plants but only 1.1 to 2.6 better than decentralized photocells.

Nevertheless, an important point is that SPS is able to deliver base load electicity for 8000 hours a year, which is not directly achievable with thermodynamics or photovoltaics. These last require either thermal or electrical storage, or contribution of other fuels.

Finally it is important to notice that photovoltaic power plants and reference concept SPS are roughly suitable for latitudes between 45 °N and 45°S. On the other hand the favorable areas for thermodynamic plants are merely situated between 10° and 40° North or South.

Scenario NOE 2100 solar mix

The NOE scenario requires 2350 Mtoe of solar energy in 2100 including thermal and electrical applications. Table IV shows a first tentative breakdown of different technologies: thermal applications, wind electricity, decentralized solar electricity, centralized electricity (power plants and SPS).

- Thermal applications: we have supposed that each house is equipped with a 0.5 m2 to 1 m2 per inhabitant area of solar thermal collectors, in relation to the local energy productivity (from 4 to 8 10^{-3} toe/m2/year).

- Wind: equipment in windy regions (> 3500 kWh/year per installed kW) with a maximum of 20% of the local needs of electricity to take into account the random aspect of the production (for instance in Europe, electricity needs are assumed to be 40% of total needs in 2100, that is 250 Mtoe, from which 60 % are consumed in windy regions, that is 150 Mtoe, where an assumed maximum of 20% could be produced by wind, that is 30 Mtoe).

- Decentralized photovoltaics: 1 m2 of photocells per inhabitant of sunny regions (> 1400 kWh/year) for rural suburban or urban single or semi collective housing (for example 30 % of the European population is concerned with these off and on grid applications).

- Centralized electricity: we consider centralized solar electricity as the difference between the total needs of solar electricity and the potential contribution of wind and decentralized solar electricity even if it is connected to the grid (typically photocells on each house). Indeed, it appears that wind technology is already cheaper than solar power plants or SPS. On the other hand, the cost of decentralised photovoltaic will stick to the cost of the principal component, the cell, whose cost should fall dramatically after 2000. This is not the case for SPS whose cost is essentially due to the launch work and space assembly cost. Further more SPS economics must take into account the cost of the antenna wich could be non negligeable compared with the support structure of a ground solar power plant field.

The last column of this table indicates the regional resultant need of ground solar power plants (GSPP) or solar power satelite (SPS) in 2100.

The main assumptions which sustain that tentative approach are the following:

Table IV: Scenario NOE 2100 solar mix

SOLAR SUPPLIES 2100 SCENARIO NOE Moe	TOTAL	THERMAL APPLIANCES	WIND	SOLAR DECENTRALISED ELECTRICITY	TOTAL SPS + SOLAR PLANTS
North America	100	15	30	6	49
Europe	70	18	30	6	16
Japan Australia N Zeal	80	15	20	5	40
USSR Central Europe	100	20	3	6	71
Latin America	250	37	20	26	167
N Africa Middle East	650	30	1	26	593
Africa	500	65	1	60	374
India	150	55	20	43	32
China	200	45	20	40	95
Asia Oceania	250	50	5	32	163
World Total	2350	350	150	250	1600

- We consider that ground solar power plants (GSPP) **will be preferentially** installed in regions where people concentrations are near enough from desert areas and sunny regions (for example Egypt, Lybia, Middle East, Australia, California and so on). Indeed , we assume that the space system will remain at least 4 to 10 times more expensive than terrestrial system. In these regions where SPS land productivity is never more than 2 to 3 times the one of solar power plants, there is no chance to become competitive with earth based plants while the price of photocells falls down. However it could be the case in crowded areas where sunny sites and other fossil or renewable energies are not available, for example in equatorial West Africa or South East Asia cloudy regions with very high foreseen population densities (> 1000 inhabitants/km2).

Under these assumptions, table V shows a possible regional distribution for GSPP and SPS by 2100. Standard units of 10 km per 10 km ground power plants have been selected, since they are supposed to have a 5 MW peak output such as SPS, and about one fourth of SPS annual energy production (10 TWh versus 40 TWh).

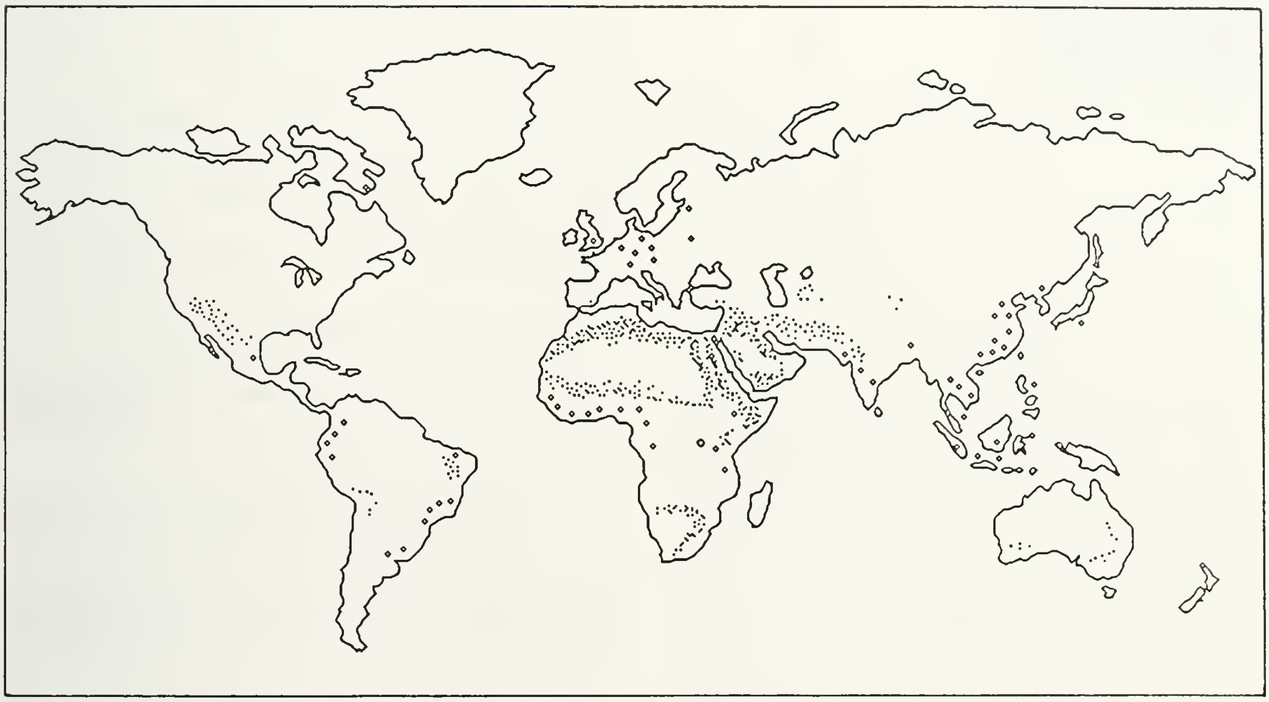
Table V: Ground solar power plants and solar power satellites by 2100

SOLAR SPS AND TERRESTRIAL POWER PLANTS 2100 SCENARIO NOE TWh	TOTAL TWh	GROUND TWh	NUMBER OF SITES 10 km*10 km 5 GW (10 TWh)	km2	SPATIAL TWh	NUMBER OF satellites 5 GW (40 TWh)	km2
North America	220	220	22	2200	0	0	0
Europe	70	30	3	300	40	1	150
Japan Australia N Zeal	180	140	14	1400	40	1	150
USSR Central Europe	320	80	8	800	240	6	900
Latin America	750	270	27	2700	480	12	1800
N Africa Middle East	2670	2670	267	26700	0	0	0
Africa	1680	1680	140	14000	280	7	1050
India	150	70	7	700	80	2	300
China	430	30	3	300	400	10	1500
Asia Oceania	730	130	13	1300	600	15	2250
World Total	7200	5320	504	50400	2160	54	8100

The map given figure 3 is an illustration of this distribution:

- each . represents a 10 km per 10 km solar power plant unit,
- each ◊ represents one SPS antenna.

Fig. 3: Map of ground solar power plants and antenna for SPS by 2100



Conclusion

Begining with a long-term evaluation of energy needs which takes into account a sustained effort toward energy efficiency and conservation, NOE scenario points out the importance of renewable energies for a sustainable world energy supply.

Among those renewables, solar energy can contribute significantly by decentralized systems, grid connected solar plants and solar power satellites.

The map of ground solar power plants and reception antenna for solar power satellites (figure 3), although indicative, gives rise to some comments:

- Ground solar power plants produce two times more electricity in the world than solar power satelites in 2100. They never require more than 1% of the desert areas of the concerned regions. Even in North Africa and Middle East where we propose a very great number of GSPP, the land requirement remains less than 10^{-3} of the desertic areas.

- It appears clearly that the only real need for SPS comes from present developing countries, since they totalise 46 from the 54 units proposed in 2100.

- The five principal regions where SPS looks like a potential long term solution are Asia Oceania, Latin America, India, China and West tropical Africa. All of these countries will experiment huge needs of electricity **if the population and development projections of our scenario are correct**. They will represent at that time 8,4 billion inhabitants, with densities often more than 1000 inhabitants per km2.

So it appears clearly that this type of technology has no chance to be developed if there is not:

- Either a very important domestic self development of industrial capacities from the South countries to build by themselves original spatial technologies,

- Or a huge effort from present industrialized countries to build and transfer very sophisticated technologies to the third world, since cheaper and environment safe terrestrial solar solutions could be implemented for the North alone, without insuperable difficulties.

Indeed, one could say that these conclusions were included in the main assumptions of our scenario, since a real development of Southern countries and a considerable effort of Northern countries to promote energy efficiency, and first at home, are the basic options of these projections. If the first assumption were not verified in the long term, it's the political and social equilibrium of the world which could be in fact questionned. If development occurs, but energy efficiency does not come with, the problems of environment, reserves depletion and energy production financing will become so enormous that there will be hardly any room for any new, expensive and sophisticated technologies such as SPS.

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A2.2 A different race: Global Rural Electrification, Market niches, the Third World as a starting place for SPS

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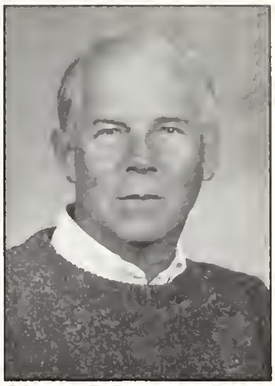

ABSTRACT

Global Rural Electrification is a proposal to use energy from space under a program of energy as foreign aid to provide electricity to the rural poor of the developing countries as a way to benefit the global environment. Market Niches are needed for the SPS technology to prove itself and secure the time needed to achieve the economies of the learning curve. The developing nations provide such a market niche and include the economic benefit of having higher cost per kilowatt-hour for conventional generation thus making satellite power economically competitive early in its development cycle. A Different Race is the philosophy of using the development of space for the benefit of humanity as an alternative to the arms race.

RESUME

L'électrification rurale globale est un projet d'utilisation de l'énergie venue de l'espace à double objectif: d'une part il represente une aide étrangère afin de procurer l'électricite aux campagnes demunies des pays en voie de développment; d'autre part, il constitute un progrès en matière d'environnement. Une condition nécessaire au project SPS est représentée par les niches de Marché: elles prouveront la crédibilité de sa technologie en même temps qu' elles laissent suffisamment de temps aux économies pour réussir leur phase d'apprentissage. Les pays en voie de développement constituent une telle niche de Marché, avec notamment l'avantage économique suivant: le prix élevé du kilowatt.heure de l'électricité classique permet de rendre l'energie transmise par les satellites competitive sur un plan économique, alors que ceux-ce ne seront encore que dans leur phase de developpement. Une Course Différente, c'est la philosophie d'utiliser le developpement spatial pour le bienfait de l'humanite plutôt que la course à l'armement.

Introduction

Perhaps the single greatest contribution that could be made to environmental conservation would be the invention of a satisfactory fuel-wood substitute for the rural population of developing countries. The rural poor of the Third World are a market in need of energy even if the customers do not have the hard currency needed to pay for it. Tthey do, however, have a product that at least the popular press indicates the industrialized nations are willing to talk about if not pay for-preservation of the environment.

If implemented with care and appropriate technology, a program of energy from space as foreign aid could reverse trends toward desertification and deforestation in the Third World. The customer, the peasant and farmer of the third world, may be able to afford energy from space if the industrialized nations are willing to grant environmental credits for using the energy in lieu of biomass or fossil

fuels. After all some industrialized nations are talking of taxing emissions so why not indirect tax subsidies for avoiding the use of fossil fuels or forest products altogether.

This paper is a discussion of the possibility of implementing as a means to combat global warming and perserve the environment a program of global rural electrification using power from space provided to the Thrid World as foreign aid. The program would be financed by running a different race than the arms race - a race for the environment which would use the human, technicological and financial resources which to date have been spent on strategic weapons systems. Such an undertaking would provide the market niche or toehold needed to implement the Solar Power Satellite program.

Background

The lack of a willing suitor or market niche defeated previous proposals to build satellite power systems. The SPS's of the 70's followed NASA's cult of giantism. They were huge in scale and posed a direct and immediate threat to special interests such as coal, nuclear power and private utilities. Given the developing public distrust of huge government programs, the Viet Nam War and Nuclear Power, during the 70's, the lack of support, almost resistance, from vested interests doomed the 5 to 10 gigawatt systems and a100 billion dollar R&D effort proposed by NASA and the aerospace industry in the late 70's.

In order for satellite power systems to become a viable energy option an appropriate **market niche** must be found where it does not directly, in the near term at least, threaten vested interests, overly alarm the population and provides humanitarian and environmental benefits. The market niche must also allow or demand tangible, visible successes every 2 to 4 years. The R&D effort must result in, very short order, projects which can be written about in the popular press.

The **Third World** is with its high energy costs and a lack of vested interests interested in maintaining the dominance of coal or nuclear power an ideal market niche for introducing subsidized energy from space. Other factors favoring the developing nations as a potential first market are its need for small, modular increments of power and the declining sources of biomass for use as fuel for heating and cooking. A program of **global rural electrification** could be imple-mented based on satellite power systems using either high frequency, 60 to 100 GHz, or tightly focused microwave energy to transmit the necessary electrical energy to rural regions around the world.

In order to fund the research and development and to provide a subsidy for underwriting energy as foreign aid, money must be found in already tight budgets. This search for funds must rely more on creating a new paradigm or way of thinking than finding a new source of revenue or increased deficits. The need to maintain a cadre of technical trained individuals in the face of declining budgets and changing defense environments offers nations which can deal with the concept of an industrial and economic policy a chance to run ***A Different Race.*** An economic term for a different race is space Keynesianism as opposed to military Keynesianism. This concept is described in greater detail in a paper on Space as a Strategic Alternative, Leonard, 1988b. An earlier, 1980, reference is also listed.

By funding the development of satellite power instead of putting more money into the capital consuming defense industry a nation can maintain and enhance a strategic deterrent capability based partly on knowledge and economic competitiveness rather than pure fear. Both the U.S. and the U.S.S.R have stumbled economically into the black hole of defense which consumes the muscle of an industrial nation, capital.

The companies and personnel needed to develop satellite power systems are for the most part the same as those needed to build defense products and facilities. However, any new major space program in order to have the support of the public and politicans will have to reach beyond the old boys school of space agencies and aerospace. New coalitions will have to be formed with other industrial partners and government agencies. Some may even have to have the lead if the concept is to win through the maze of special interest groups.

The components of satellite power for the third world; power beaming, tight beams, long distance command and control of satellites, construction in space and heavy lift launch vehicles are the very same ones needed for strategic or tactical ballistic missile defense. Consequently, a nation can run a different race, a race to save the environment, while maintaining the technological capabilities needed for deterrence of other industrialized nations by investing in the development of power from space.

Market Development

Any new product, technology or new energy source requires a way to enter the market place. Energy from space is in this regards no different than the copier, the railroad or the oil industry. The question is where is the market niche for SPS given the entrenched and vested interests of the various "conventional" energy sources such as oil, coal and nuclear in the industrial nations and advocacy groups.

Time to maturity

New industries also require a period of time for the absolute rate of capital formation, i.e. the rate of growth, to acquire a large enough capital base for rapid expansion. Such growth is a function of both the re-investment of profits, i.e. the success of the technology, and the willingness of the financial community to provide capital (investment) based on anticipated profits.

According to Starr and Searl, 1990, there is a historical time constant of a half-century for substantial changes in the mix of large scale energy systems. This is in keeping with both the planned life expectancy of generation facilities (30 years) and the rate of capital formation that takes place within a new industry. It also fits with the 17 year cycle required for new ideas to penetrate existing power structures and to start to have an effect on the younger decisionmakers moving into power positions.

This time constant along with the historical rates for capital formation should be taken as a warning by those advocates of gigawatt plants and premature macroprojects. We need to think about were we are going but if we will only be satisfied with gigantic projects we will be doomed to live with dreams rather than hardware. Four billion for the development of a new North Seas oil field, a product with known if somewhat variable price and profit. Billion dollar gigawatt power plants are not to popular with the utilities right now even those financially healthy enough to swallow one. Consequently, given the above, if we hope to see rapid implementation of a new technology such as the SPS concept and see it have a dramatic environmental impact we will have to look elsewhere than the industrial nations for an initial market.

My criteria for a market niche for energy for space is that there has to be a need for small amounts of power and furnishing that power had to convey a tangible or intangible benefit to the developers, underwriters and the users. The developing nations, their need for energy and the impact on the environment that their lack of energy has, offers both a starting place and a justifying reasons. The developing nations offer a market in which we, the advocates of energy from space, can show success from small projects.

Characteristics of the Market

I will narrow the market focus even more by looking at applications for energy from space in the area of rural electrification. It is a market in desperate need of energy and is also a market free of special interests trying to maintain a monopoly or protect a vested interest. Once the concept is proved successful in rural areas it will be fairly easy to work with the established utilities in the developing countries to gradually link the remote nodes together. Energy from space, initially in small units of power, offers countries the means to achieve a balanced, robust energy system composed of central and distributed generating facilities.

The attributes needed for market penetration by energy from space are similar to those for terrestrial photovoltaics. In fact the two options, microwave power and terrestrial solar electric, complement each other. One provides a base load capability while the other can be used at very remote sites.

Hoffman and Byrne, 1991, in their summary of terrestrial photovoltaics highlight benefits which would be similar for energy from space. These are:

- The need to limit hard currency expenditures for diesel fuel for remote generators.
- The technology is capable of being scaled in a modular fashion and can thus be fit to social needs and local organizations.
- The use of energy from space would provide a socially acceptable alternative to fuelwood thus greatly limiting the environmental damage

To this list Singh, 1991, adds that the main advantages of a solar electric technology over diesel generator systems are:

- Low maintenance requirements
- No fuel requirements
- High reliability
- Long lifetime (> 20 years)

- Lower life cycle system costs (this needs to be documented).

The ground station technology is passive and modular. This latter factor allows smaller systems to be built and expanded to meet larger loads. In the case of microwave power the growth can be accomplished by either increasing the area of the receiver or up to the environmental limit increasing the power density of the beam.

A requirement for the successful demonstration and initial use of SPS power is a remote location which has a reasonable organizational structure and is familiar with technology. The author in 1988, Leonard, 1988a, proposed working with mission hospitals located in Africa. Singh, 1991, points out that the regional health and administrative centers in Kenya are also good candidates for the potential application of solar electric systems because of the difficulties of providing fuel to these remote locations. Another possibility would be the headquarters of a game preserve perhaps one co-located with tourist facilities.

Likelihood of Market

Hansen, 1987, reports that solar electrification has been successfully implementation at a local level in the Dominican Republic in an independent, private and decentralized development program. Here the power has been used to displace kerosene for lamps and batteries for powering radios and television sets.

Subsequent to the presentation of his paper in India, the author has had discussions with government officials in both China and India on the possibility of establishing a demonstration project. The gist of those conversations is that if I have the money and a system they will provide a site for testing and demonstration.

Consequently, it seems that if technical, political and funding problems can be overcome it will be possible to initiate market development of satellite power systems in a developing country, perhaps even more than one. A condition I would like to impose on the demonstration is that it cannot be like the ATS educational television demonstration in India where you prove your point and then take the technology away. If we give a village or regional health center a power system based on satellite power technology I feel we are obligated to leave that system in place operating for at least the lifetime of the satellite.

Growth of the Market

Singh, 1991, reports on the work done by Milanesi with respect to the tradeoff between extending the grid from a central power plant and using stand alone diesel generators. Table 1 summarizes those results. Given this table and the above discussion we can define the ideal first site for demonstrating energy from space. A site which will hopefully have growth potential.

Table 1 Breakeven Distances for Grid Extension versus Stand Alone Generation.

Power Level (kW-hr)	Distance (kilometer)
200,000.	45
500,000.	63.5
1,000,000.	95.

The Ideal First Site

The ideal first site will have a need for 10 to 100 kilowatts of power. The power is sized for either a Soviet Topaz II space nuclear reactor (12 kW) or the use of terrestrial solar cells launched on a Proton. The site will be remote but with good access by roads and small airplanes. There will plenty of land around for both expansion and for agricultural experiments on the long term effects of microwave energy. An additional feature would be the potential for large scale growth such as might be provided by a mine, smelter or processing plant. On the other hand looking at Table 1 we could have a site located about 100 kilometers from a large city and plan to eventually hook the space power system into the national grid.

Market Match with Technology

For global rural electrification to be technically feasible we need either clever antenna design if we stay at 2.45 GHz or we need to move to higher frequencies. At higher frequencies the size of the ground antenna is reduced to a diameter that is compatible with power in the range of 100 to 1,000 kilowatts. This is an attractive power level because it is compatible with the payload capacities of current available launch vehicles, available satellite technology and the amount of risk capital needed from the industrial countries. Table 1 from Leonard, 1991, is a tabulation of antenna size as a function of frequency for diffraction limited planar arrays.

Table 2 Antenna Size as a function of frequency.

Frequency (GHz)	Wave length (cm)	Transmitter (meters)	Receiver (kilometer)	Approximate Max. Power Received(MW)
2.5	11.99	1,000. 100.	4.30 43.04	3,340.0
10.0	3.00	1,000. 100.	1.08 10.77	210.7
50.0	0.60	1,000. 100.	0.22 2.15	835.0
100.0	0.30	1,000. 100.	0.11 1.08	2.2 210.7

Are Developing Countries a Viable Market Niche?

There is a great deal of similarity in the problems facing market penetration by solar power satellites and terrestrial photovoltaic technology. Hoffman and Byrne, 1991, and Singh, 1991, both present reasons for the failure of a market to develop in terrestrial photovoltaic (PV) power systems in the Third World. Some of those reasons are: lack of foreign exchange, and the absence of the infrastructure needed to support the technology. Other reasons are given below.

Self Created Hurdles

The success of social and economic growth in the developing countries has depended upon the people being able to absorb and apply the technologies that the more advanced countries had created (Vernon, 1989). Vernon points out that although polices may create an environment which impedes or encourages development it is the role of the people, the managers and technicians which are critical in determining the outcome.

De Soto, 1991, reinforces Vernon's statement in his work, *The Other Path*, which documents the growth of the shadow economy of Peru as a function of the hassle factor of having to deal with the government. De Soto documents that the impediments to growth and the assimilation of new technology in the third world reside in what is essentially a mercantilist economy. Here, quoting from the forward to De Soto's book, mercantilism means a bureaucratized and law-ridden state that regards the redistribution of national wealth as more important than the production (or creation) of wealth.

The mercantile system is self-perpetuating in that the officials, managers and technicians for the most part see it as a way to better themselves through bribes and commissions. It is a system which condemns a country to underdevelopment and will slowly drown in its own inefficiency and corruption, De Soto, 1989. Perhaps this hurdle can be finesse by working either directly with local leaders in a village or with a semi-independent organization such as a relief group or mission hospital. Another possibility is that once an SPS system is built government officials almost no choice but to let the power be used by the people, otherwise there is no source of revenue.

Hurdles of perception

Singh, 1991, cites the perception that PV technology is a technology of the future and is to expensive. This is the same perception which plagues the SPS concept. However, at least terrestrial solar electric occasionally gets mentioned in the popular press as an energy alternative. We have a long way to go to create public awareness of the SPS energy option.

Hurdles from the Advocates

If advocates of solar power satellites continue to insist upon 100 billion dollar research programs, 5 gigawatt satellites and trillion dollar lunar power systems without offering the public a path of gradual steps the public will not finance their technological fantasies. This unwillingness on the part of advocates to begin small and drive to the successful completion of a small, perhaps even technical primitive and non-optimum demonstration is perhaps the biggest hurdle facing SPS. If we cannot overcome our desire for technological giantism SPS will go the way of O'Neil's Space Colonies, NASA's Space Station Freedom and President Bush's 30 year program to send a man to Mars.

Clearing the Hurdles

Energy as foreign aid, which may be feasible for SPS because of its space based component and not for terrestrial photovoltaics, is a partial answer to the lack of foreign exchange. The lack of a need for a storage system and the passive nature of the receiver reduces the need for an in-country infrastructure to support the technology.

The perception that the technology is for the future is our fault for only describing giant systems and all the research that must be done. In the question of costs we have giving the playing field to our critics and opponents. This is due in part because in our hearts we want the big front end research projects and if we start deploying low cost systems we won't get the money for more paper studies.

Global Rural Electrification

We have a market but how do we justify developing the product to sell to the market. I suggest that a program of global rural electrification based on the using energy from space as a way to benefit the environment and provide a means for sustainable development, paper SPS-91.60, provides the rationale for such an undertaking. This program is based on:

- Energy as foreign aid
- Electric power from geosynchronous orbit distributed to individual villages via microwaves for a cost of between 6 cents and 45 cents per kilowatt-hour in modular increments of 25 to 100 kilowatts with an average capital cost as low as $5,000 per kilowatt.
- A Different Race: Space as a strategic alternative to the arms race and as a way of financing global rural electrification.

Why focus on Developing Countries?

Although today developing countries contribute a far smaller per capita share of greenhouse gases than the industrialized nations, most of the future increase is likely to come from those countries unless alternatives to coal, oil and wood are provided to them. China alone is contemplating building over 200 coal-fired powerplants over the next 30 years. Consequently, unless the industrialized nations address the developing nations needs for energy by creating an environmentally benign source of energy their efforts at home to save the environment will be overwhelmed by the efforts of the poor to survive.

Competition, Near and Far Term

What are the competing energy technologies. Currently, oil, gas, coal and nuclear power all compete in the power generation market. Within the rural markets of the third world there is competition from biomass. However this is rapidly being exhausted and for remote, isolated sites terrestrial photovoltaics and wind. The last two choices are highly dependent upon the climate.

Burning fossil fuels for power generation has a very adverse impact on the environment. Fossil furels also require a never ending source of hard currency.

In spite of the claims by its advocates such as Starr and Searl, 1990, it is doubtful that nuclear power can either be scaled up or will be allowed to completely replace fossil fuels given public concerns about safety and waste disposal. In addition the technology required to build an operate nuclear plants along with the foreign exchange needed to purchase them probably precludes many of the developing nations from utilizing nuclear energy as an alternative to fossil fuels.

Conversion to energy from space, if we can overcome the hurdles, will become economic as oil reserves are depleted, acid rain from coal continues to poison lakes and even oceans and global warming from CO2 buildup makes itself felt. There are no easy choices but SPS power appears to be one of the better ones.

Economics and Financing

One of the many reasons for looking at rural electrification as a market niche is the fact that the cost of power, not the price of power charged the peasant, is considerably higher than that charged either the urban dweller or citizen of an industrialized nation. Barnes, 1988, reports costs as high as 55 cents per kilowatt-hour for places (Andhra Pradesh) in India. Calculations by Leonard, 1991, indicate the cost of power from stand alone diesel generators at between 10 and 25 cents per kilowatt-hour. Table 3 lists the cost of power from different size size generators based on 1984 data contained in Means Construction Cost Data. The operating cost is very dependent upon fuel costs and the operation is very dependent upon having fuel available along with a mechanic who can maintain the unit.

In previous work, Leonard, 1991, as well as several other papers being presented at this conference, SPS-91.58 and .61 the author documents a stepwise system for achieving power costs competitive with those listed in Table 3. Table 4, which is taken from Leonard, 1991, tabulates those costs. The reader wishing more details on the author's assumptions is referred to the three papers cited.

The data in Table 4, which is based on two crucial assumptions, using terrestrial photovoltaics for their price and accepting the weight penalty and use of a Soviet PROTON launcher, indicates that by 1998 power from solar power satellites would start to be competitive with the cost of power in various rural areas of developing countries. This assumes that there is no escalation in the cost of fuel and that fuel is available. Some where around 2001 the systems become competitive with central plant power without any credits for not having to build transmission lines.

Table 3 - Cost of Electricity from Portable Generators

Size of Generator kilowatts	Type of Fuel	Operating Cost per kilowatt-hour	Equipment Cost per kilowatt hour	Total Cost per kilowatt hour
5.	Gasoline	16.40	25.89	42.29
10.	Gasoline	19.30	37.79	57.09
20.	Diesel	16.25	28.07	44.32
25.	Gasoline	14.56	12.82	27.38
50.	Diesel	7.00	14.36	21.36
100.	Diesel	8.10	13.96	22.06
250.	Diesel	5.64	4.03	9.67

Table 4 - Declining Cost of a System as a function of weight and cost reductions for solar cells and declining launch costs.

Year	Installed cost ($/kW)	Cost per kw-hr (cents)
Today	998,260.	1,233.54 ($12.34)
1994	288,600.	356.60
1996	147,000.	181.60
1998	47,680.	58.92
2000	27,470.	33.94
2002	9,630.	11.89
2004	4,965.	6.13
DOE/NASA Reference Sys.	4,800.	5.93

Asuming that small antenna can be developed then we are looking at about 150 to 200 million for a 100 kw prototype system. The cost of follow on systems will depend upon launch costs and the cost and weight of solar cells. Assuming both a subsidy for launch costs under the energy as foreign aid program and low interest loans from lending agencies such as the World Bank the cost of power from space should be very competititve in 100 kilowatt chunks.

Conclusions

The rural areas of developing countries are from the standpoint of need a viable market niche for power from space provided the problem of antenna sizing can be solved. The technology provides a way to create nodes of power and development. For the technology to be accepted will require a change in the habits and thinking of government managers and technicians within the developing countries.

The only way this market will be developed is if the industrialized nations consider providing energy from space as a form of foreign aid. This requires governments of the industrialized nations to consider running a different race where they fund the development of the infrastructure needed to make them a spacefaring nation rather continue to fund strategic weapons systems.

The Third World offers a starting place for power from space. The environmental benefits (SPS-91.60) of power from space offers a strong moral justification for the industrialized nations to undertake a test and evaluation program now.

The U.S. Department of Energy has issued a white paper entitled Energy Technology for Developing Countries: Issues for the U. S. National Energy Strategy, which in part states the U.S. could do more, if it so chooses to, to help the developing countries with their energy policies. Admiral Watkins is on record as stating that we must develop environmentally benign sources of energy. There is a recognition of a problem and SPS, if its case can be presented and made to the public and the legislators holding the purse strings, can be a partial solution to the questions of sustainable development in the third world and the mitigation of environmental damage caused by development.

Acknowledgements

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Related Work

This paper is one of four presented at the SPS 91 Conference. Their relationship is described below. Together they describe a vision for the future and a reasonable path which may be taken to transform that vision into reality

SPS-91.60, The Environmental Benefits of Solar Power Satellites, establishes an ethical and environmental rationale for utilizing the resources of Greater Earth to provide energy from space.

SPS-91.59, A Different Race: Global Rural Electrification Market Niches and the Third World as a Starting Place, this paper, describes a program for evolving the power satellites from small systems which we know how to do now to larger systems which we will know how to when the time comes. This paper extends the environmental rationale established in PS-91.60 to the economic domain and presents the concepts of energy as foreign aid and energy from space as a strategic alternative to the arms race.

SPS-91.58, Economic Impact of Using Lunar Resources to Build SPS Systems, assumes that the demonstration project, SPS-91-61, has been successful and that systems have been scaled up to meet the needs described in SPS-91.59. It also builds on the environmental concerns described in SPS-91.60 and leads one in a logical fashion to the cost effectiveness of using lunar materials.

SPS-91.61, The IGRE's 100 Kilowatt Demonstration Project, describes several low cost demonstration projects which will provide proof of principle demonstration, a technology test bed, and be the first steps in series o gradually increasing larger satellites. The project is design to be accomplished within 4 years for less than 250 million dollars. A secondary purpose is to excite the public and an stimulate in youth an interest in science and engineering.

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SPS 91

A2.3 The nuclear power satellite (NPS) - Key to a sustainable global energy economy and solar system civilization

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ABSTRACT

This paper introduces a parallel role for an evolutionary family of nuclear power satellites (NPS) both in the development of a sustainable global energy economy for the planet Earth and in the development of a Solar System civilization which will include (in time) a permanent human presence on the Moon, on Mars, within the asteroid belt, and even within the resource-rich Jovian and Saturnian systems. The technical steps needed to develop, operate, maintain, transition, and post-operationally decommission multimegawatt to gigawatt class space nuclear facilities are described in the context of an emerging 21st century space technology infrastructure. Also discussed is a very important initial application of the nuclear power satellite which involves linking its energy output via energy beaming to hydrogen energy parks on Earth - providing our planet with an environmentally benign supply of both electricity and liquid fuel for transportation and energy storage.

RESUME

Ce document introduit le rôle parallèle d'une classe évolutionnaire de satellites de puissance nucléaire (SPN) tant dans le développement d'une économie soutenue d'énergie globale destinée à la planète Terre que dans le développement d'une civilisation du système solaire qui comprendra éventuellement une présence humaine permanente sur la Lune, sur Mars, à l'intérieur de la ceinture d'astéroïdes, et dans les systèmes Joviens et Saturniens riches en ressources naturelles. Les étapes technologiques nécessaires pour développer, opérer, maintenir, changer, et par la suite, éliminer de telles installations nucléaires spatiales, des puissances de multi-mégawatts à un gigawatt, sont décrites dans le contexte d'une infrastructure de technologies spatiales pour le XXI siècle. Ce document adresse également l'importance initiale d'une application de satellite de puissance nucléaire qui demandera l'enchaînement de sa production d'énergie, par l'émission de rayons, sur les parcs énergétiques Terrestres de production d'Hydrogène afin de fournir notre planète d'une source bénigne sur le plan environnemental, source d'électricité et de combustible liquide pour la transportation et l'accumulation d'énergie.

I. Introduction

A significant number of advanced space missions have been identified that need versatile, high-capacity space nuclear power systems [1-3]. These missions include: manned planetary outposts and bases essentially requiring hundreds of kilowatts to megawatt power levels for sustained operations; interplanetary electric propulsion cargo vehicles with requirements in the 2 to 5 megawatt power range; and Earth-oriented applications (such as very high capacity communications and information processing platforms in geosynchronous orbit and industrial-scale microgravity materials processing facilities in low Earth orbit) with anticipated requirements of hundreds of kilowatts-electric. Figure 1 describes the planetary surface power requirements for a variety of future manned missions to the Moon and Mars [1-3].

The entire spectrum of "classical" nuclear propulsion concepts, as shown in Figure 2, is also being given renewed interest and study - both in support of human expeditions to Mars and in support of ambitious robotic missions to the outer regions of the Solar System and beyond (e.g., the Thousand Astronomical Unit (TAU) mission) [4-5].

The significant point here is simply this: the development of humanity's extraterrestrial civilization and the full and complete exploration of our Solar System will be accompanied by the extensive use of progressively more sophisticated space nuclear power systems, including advanced fission reactors and (in time) controlled thermonuclear fusion systems. Within the first few decades of the 21st century, therefore, a space technology infrastructure will emerge which will ensure the safe, efficient and beneficial operation of these space nuclear systems - including careful attention to post-operational disposal issues and immediate response to potential abnormal situations that could impact the terrestrial biosphere [6-7]. Can our investment in this aerospace nuclear technology infrastructure play a parallel role in helping resolve critical terrestrial energy needs/environmental burden circumstances? The affirmative answer is called: the **Nuclear Power Satellite (NPS)**.

II. The Nuclear Power Satellite

The Nuclear Power Satellite (NPS) is essentially a spacebased energy center that uses the nuclear fission or nuclear fusion process to make available large quantites of energy in a very compact, mobile facility. (See **Figure 3**) It is important to recognize that the Nuclear Power Satellite will not only provide prime electric power in large quantities (gigawatt-electric regime), but also could represent a source of process heat and a neutron source for radioisotope production and the breeding of additional nuclear fuels (such as tritium for spacebased fusion systems and uranium-233 for spacebased fission systems). Societal investment in the Nuclear Power Satellite at the start of the 21st Century will help resolve long-term global energy needs (i.e., NPS power beaming to hydrogen energy parks on Earth) in an environmentally benign way and will also open up the entire Solar System to human development. This is a significant parallel role for the NPS.

The Nuclear Power Satellite concept was only briefly addressed in the late 1970s and then (essentially mimicking the overall retrenchment concerning space nuclear power and propulsion systems that occurred in the US space program in the 1970s) was abruptly dismissed without serious analysis.

"The orbiting nuclear reactor concept has been evaluated to a limited extent. While it might offer the advantage of compactness relative to solar powered systems....significant safety and environmental questions remain to be addressed." [8]

However, as interest in space nuclear power systems returned to the US space program in the 1980s, the Nuclear Power Satellite concept has once again emerged. **Figure 4** presents a montage of several recent NPS concepts, involving energy-beaming both in the form of microwave and optical (laser) transmissions [9].

As described in **Figure 5**, the Nuclear Power Satellite has several key attributes including compactness and its ability to operate at full capacity anywhere in the Solar System (and beyond-when necessary). The Nuclear Power Satellite emerging in the 21st Century will actually be an evolutionary series of systems: starting with advanced solid core fission reactors (multimegawatt class-prototypes), maturing into more energetic (gigawatt class) gas core fission reactors, and eventually evolving into a class of controlled thermonuclear reactor systems which will culminate with helium-3 burning systems (i.e., $^3He + D$). One particular advantage of the fusion reactor system over the fission reactor system will be its much more favorable neutron economy. As shown in **Figure 6**, many times more excess neutrons could be produced within a fusion-powered NPS than within an equally energetic fission-powered NPS. These excess neutrons will permit the spacebased production of many useful radionuclides by fusion-powered NPS systems.

Figure 7 illustrates a one-gigawatt-electric class NPS based on an advanced gas core fission reactor [10]. It is important to appreciate the very compact nature of the NPS. In the system shown, the gas core reactor is dwarfed by its thermal radiator subsystem (each panel is about 50 meters by 27 meters), while the RF transmitter array (to beam power to a terrestrial or extraterrestrial location) is on the order of a fifth of a kilometer in length and width.

III. NPS Power Generation Stages

Parameters that are important in selecting a nuclear fission power plant during a pilot NPS demonstration phase include:
- the system mass should be kept sufficiently low to achieve a pilot demonstration plant configuration with a minimum number of heavy lift launch vehicles;
- the overall system size will also be constrained by launch vehicle considerations;
- the system lifetime should be on the order of thirty years, making it similar in lifetime to central power station plants on Earth;

- on-orbit assembly and maintenance operations should require a minimum amount of direct human participation to minimize costs and astronaut risks;
- aerospace nuclear safety must be assured during all pilot plant mission phases, including launch and assembly, operation and maintenance, and decommissioning and disposal;
- the proper space disposal of the spent nuclear fuel/waste materials and the overall decommissioning of the pilot power plant should be considered from inception of the design;
- the system's impact (e.g., potential effluents and stray nuclear radiation emissions) upon the space environment and other space systems must be rendered negligible; and
- the cost of power delivered to Earth must be competitive with terrestrial power systems.

To achieve this set of parameters, a high temperature, gas core nuclear reactor coupled with a magnetohydrodynamics (MHD) power conversion system was selected for the NPS pilot demonstration plant. Research is currently being conducted in the United States to establish the technical feasibility of such a system and to validate its engineering characteristics [11-14]. One concept now being evaluated, as shown in Figure 8 [11-14], uses an ultrahigh temperature vapor core (UTVC) coupled with a compact magnetohydrodynamic (MHD) power conversion system. (The nomenclature associated with this figure is as follows: MBEO = mid-plane BeO region; IBEO = inner BeO region; TBEO = top BeO region; OBEO = outer BeO region; and LBEO = lower BeO region [14].) The proposed working fluid/fuel is a vapor mixture of UF_4 (approximately 10%) and potassium fluoride (approximately 90%) in the partially ionized state. An external beryllium oxide (BeO) moderator is used to minimize the core size. This vapor mixture has an inlet temperature on the order of 4000 K and an inlet pressure of about 5068 kPa (735 psi or 50 atm). The MHD conversion system operates in the strong interaction regime (i.e. magnetic Reynold's number approximately one) to maximize power density.

Figure 9 illustrates some typical operating conditions for this type power plant [12]. Although the reactor outlet temperature is 4000 K, the reactor walls are maintained at about 2000 K by the tangential injection into the reactor core of liquid metal fluoride. As this metal fluoride is injected into the UTVC, an annular buffer zone is obtained which helps keep the UF_4 away from the UTVC walls. This also reduces the possibility that uranium or uranium compounds will condense on the UTVC wall. Once beyond this buffer zone, the injected metal fluoride vaporizes and mixes with the UF_4 in the UTVC.

By configuring the disk MHD generator as an integral part of the reactor (as shown in Figure 8), a significant amount of fissioning occurs throughout the disk generator region. This helps maintain the necessary electrical conductivity, despite the relatively low fluid temperatures.

Reactivity changes associated with changes in the volume of the liquid fuel/working fluid mixture in the boiler columns tend to stabilize the system. For example, if the power level of the system should increase, the amount of liquid in the boiler regions is reduced and more vapor (or void spaces) is present. This causes a negative reactivity insertion and a drop in the power level. The amount of this negative reactivity feedback depends strongly on neutronic coupling between the UF_4 boiler columns and the UTVC.

The mass of a pilot 1 GWe system is on the order of 450 Mg. The radiator is the dominant system component with a mass of approximately 230 Mg and a size of about 0.1 km^2 for a radiator temperature of 1600 K. This pilot NPS plant is designed for automatic (teleoperational) assembly on orbit. For example, once in orbit, the radiator will be deployed automatically. Robot systems (teleoperated from Earth) will then be used to assemble the radiator to the nuclear reactor and power conmversion system.

Shielding, which can be made from lunar raw materials, will be used to minimize the amount of nuclear radiation leaking into the space environment around the NPS. Use of lunar materials for shielding permits the development of very thick radiation attenuation shields with little launch-from-Earth mass penalties. (See **Figure 10**) [9]

As part of overall aerospace nuclear safety strategies, this reactor's nuclear fuel would be launched from Earth separately; continuous refueling of the reactor over its multi-decade operational lifetime is also planned. As a rule of thumb, the reactor consumes approximately one gram of uranium-235 fuel for each megawatt-day of thermal power liberated. For example, a continuously operating 4 GWth NPS will burn less than 2 Mg of uranium-235 per annum. During operation, a portion of the working fluid will be extracted from the loop and fission products separated. Alternatively, a cyclone separator element could be added to the loop to separate the fission products from the fuel. The unburned and make-up nuclear fuel will then be added on line to replace the spent fuel. For extensive power plant maintenance and servicing, all the nuclear fuel can be quite easily removed from the gas core reactor. Once separated from the fuel, the fission products can be removed from the power plant and committed to a permanent space disposal program.

Based upon reasonable extrapolations of contemporary research and levels of demonstrated technology, a pilot gas core reactor NPS could be ready by the year 2020. This type of space reactor has the distinct advantage of not requiring extensive fuel qualification testing. Major technology issues involve the development of long-life high temperature materials, MHD generator engineering, the development of long-life high temperature radiators, and the efficient separation of fission products from a gaseous fuel stream. If desired, a demonstration NPS pilot plant could be built first on Earth to validate key concepts and engineering features, prior to in-space assembly and operation.

IV. NEP System Phase

If desired, the gas core NPS pilot plant just described could be preceded by demonstration experiments using an advanced fission space reactor power plant, perhaps the multimegawatt-class reactor system chosen to power a Mars mission cargo nuclear electric propulsion (NEP) system.

This "NEP System Phase" in the development of an operational NPS would serve the following purposes:

- engineering demonstration of power beaming from a space nuclear system to a receptor target in space (e.g., robotic spacecraft or planetary surface rover) or to a demonstration energy conversion facility on Earth;
- demonstrate the efficacy of using extraterrestrial materials (i.e., lunar soils) for radiation shielding;
- identify and scope any pressing environmental issues (terrestrial or extraterrestrial) associated with space nuclear power generation and power beaming; and
- provide an engineering data base for assessing the true economics of using an NPS to beam power to Earth.

It is especially significant to recognize that these key questions can be addressed as early as 2005, once a sufficient number of advanced space nuclear reactor power plants are available to perform such experiments. Several preliminary experiments might also be performed in low Earth orbit even before this time, if necessary.

The precise form of the fission nuclear reactor that would be used in this NEP System Phase must still be decided. However, based on contemporary programs this reactor would most likely be a solid core system consisting of cylindical, pellet or particle fuel elements and cooled by either a liquid metal or gas working fluid. Power conversion (thermal-to-electric) would involve either thermoelectric or thermionic direct conversion systems or else a dynamic conversion system based on the Rankine, Brayton or Stirling thermodynamic cycle. If an electric propulsion system is integrated into the power plant, the system could essentially "deliver itself" from low Earth orbit to geostationary orbit. No maintenance or servicing of the space nuclear power plant is planned for this phase.

Experiments to beam power to Earth could use both radiofrequency (RF) and optical (laser) technologies. RF-beaming is currently favored because it offers a higher efficiency. For example, RF generators operating at 2.45 - 245 GHz have projected efficiencies of about 90 percent, with advanced versions of these RF systems could reach 95 percent efficiency. Laser beaming appears to provide only a 20 percent overall efficiency in the same time frame [9].

V. The Global Hydrogen Economy

To ensure the availability of energy on a global basis while avoiding addition burdens to the terrestrial biosphere, it is recommended that the Nuclear Power Satellite beam its energy down to remote locations on Earth (e.g., deserted islands, uninhabited coastal regions, or artificial islands) where this beamed energy (microwave or possibly optical) is then converted into electricity AND liquid hydrogen (through electrolysis) at a **Hydrogen Energy Park** (5 GWe-class) - as is depicted in **Figure 11**.

The production of electric power at terrestrial facilities using microwave energy beamed from space has been treated extensively in the literature. We will focus, therefore, on an interesting variant of the power from space initiative. Unlike previous energy park concepts [15], the **Hydrogen Energy Park** is an environmentally benign terrestrial facility (e.g., no significant thermal pollution, no atmospheric CO_2 emissions, and no hazardous waste products). In the 21st Century, this type of remotely-located energy park could serve as the conduit for the microwave energy beamed to Earth from the Nuclear Power Satellite, effectively linking such spacebased energy systems to global energy markets using the highly versatile energy carrier - hydrogen. For example, the hydrogen shipped from this novel energy park can easily be used at energy consumer locations to generate electric power through fuel cell technology or more traditional thermogeneration approaches [16].

"Plentiful, clean, high in energy content, adaptable to power generation and to industrial, residential and transportation users" -- this statement could be the description of the perfect fuel. In fact, it is a description of the element hydrogen (H), the lightest and most abundant element in the universe [16]. Pure hydrogen is a clean fuel, its

only combustion product when burned with oxygen is water. Even when burned in air, hydrogen yields essentially no pollutants. Counterbalancing hydrogen's desirable properties is a significant natural drawback: it is rare in elemental form on Earth. Though terrestrially abundant, hydrogen is almost invariably bonded into chemical compounds. Two common examples are water (H_2O) which covers some 70 percent of the Earth's surface and all organic matter. Releasing the elemental hydrogen stored in these materials requires expending significant amounts of energy. Since energy must be invested in hydrogen before elemental hydrogen becomes useful as a clean nonpolluting fuel, hydrogen (like electricity) must really be treated as an **energy carrier** and not a primary energy source in its own right [16].

The use of electricity (another energy carrier) is widespread and growing throughout the world. But electricity is difficult to store economically, requiring the electric power industry to scale its overall generating capacity to accommodate peak demand rather than average demand. The **Hydrogen Energy Park** would take full advantage of beamed energy from space, while avoiding potential environmental difficulties that could arise if the microwave energy beam is brought down near populated regions where the demand for electricity is high. This remote energy park facility would convert incoming RF waves into electricity and then using advanced, high efficiency electrolysis processes convert some or all of this electricity into hydrogen. Cryogenic tankers and pipelines would then transport the hydrogen to markets around the world - in much the same way petroleum-based liquid fuels now feed a global energy market from several oil-rich production regions.

VI. Summary

History on Earth has demonstrated that major changes in our planetary energy system have occurred with about a one century "time constant" (i.e., wood giving way to coal as the primary energy source, coal to oil, etc..). Invoking this type of strategic planning horizon, the role of the Nuclear Power Satellite - linked to Hydrogen Energy Parks on Earth - represents an environmentally-benign, achievable global energy strategy for the planet. It is equally important to recognize that the technology infrastructure created in the development of a family of power beaming Nuclear Power Satellites also provides immediate technical and economic dividends in support of humanity's expansion into heliocentric space (and vice versa). For example, the same evolutionary family of NPS systems can become the sustainable energy supply for a human civilization on Mars (including large-scale resource development efforts and initial planetary engineering projects); for the full-scale exploitation of the asteroid belt; and for the economic development of the resource-rich worlds of the Jovian and Saturnian systems. Finally, it is interesting to recognize that in its late 21st Century configuration, an advanced NPS (using helium-3/deuterium burning and positioned in the outer regions of the Solar System) also represents the precursor power/propulsion system for humanity's first ambitious interstellar robotic probe!

In conclusion, it is most appropriate to initiate detailed technical and economic studies concerning the **Nuclear Power Satellite** in two parallel roles: linked with a global hydrogen economy here on Earth and supporting humanity's inevitable expansion off-planet into the Solar System. Both roles are integral to the realization and fulfillment of the destiny of our species in the 21st Century and beyond.

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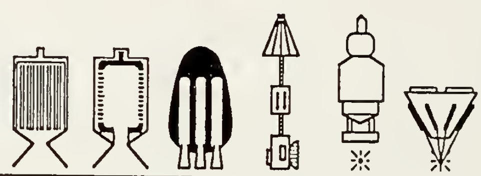
PLANETARY SURFACE POWER REQUIREMENTS
(Nuclear Reactor Applications)

Mission	Power Level	Duration
Human-Tended Lunar Observatory	< 100 kWe	Years (Sustained)
Human Outpost	100-600 kWe	Years (Sustained)
Human Base (With In-Situ Resource Processing)	2 - 20 MWe	Years (Sustained)
Human Settlement	100 MWe-1 GWe	Decades (Sustained)

Figure 1

NUCLEAR PROPULSION SYSTEMS



	FISSION SOLID CORE	FISSION PARTICLE BED	FISSION GAS CORE	FISSION ELECTRIC	FISSION PULSE	FUSION PULSE
THRUST (kN)	70	230	445	< 10^{-2}	3500	204
I_{sp} (m/s)	8430	9800	20,000	58,800	25,000	19,600
POWER (MW_t)	300	1100	4460	1-10 (th) 0.1-1 (el)	43,820	20,000
MASS (10^3 kg)	2.6	3.2	67	30-50 kg/kW_e	94	1427
THRUST/WEIGHT	2.7	7.3	0.8	< 10^{-4}	3.8	0.015

Figure 2

NUCLEAR POWER SATELLITE
(Applications)

- Electrical Power
  - Payload/Spacebased Energy Center
  - Beamed
- Process Heat
  - Extraterrestrial Materials Processing
  - Material Recycling
- Radioisotope Facility
  - Radioisotope Production
  - Nuclide Transmutation
- Precursor Interstellar Power/Propulsion System
  - Advanced Energy Technology (e.g., fusion)
  - Long Duration Operation (30-50 years)

Figure 3

NUCLEAR POWER SATELLITES
(Various Proposed Configurations)

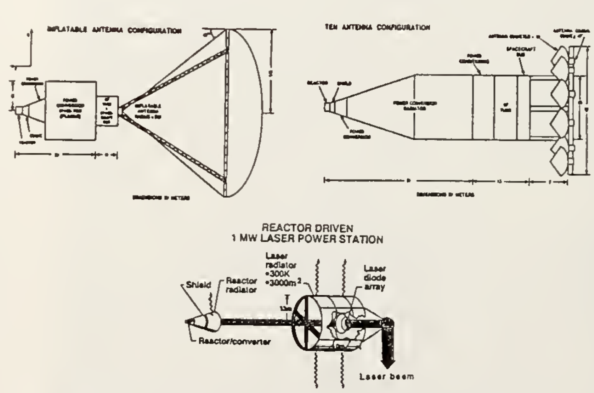


Figure 4

NUCLEAR POWER SATELLITE
(Attributes)

- Compact Energy Source
- Mobile Energy Center
- Operation Anywhere in Solar System
- Incorporates Evolving Nuclear Technologies
  - Solid Core Reactor
  - Gas Core Reactor
  - Controlled Thermonuclear Reactor
- Nuclear Fuel Cycle Off-Planet
- Precursor Energy Technology for Deep Space/ Interstellar Missions

Figure 5

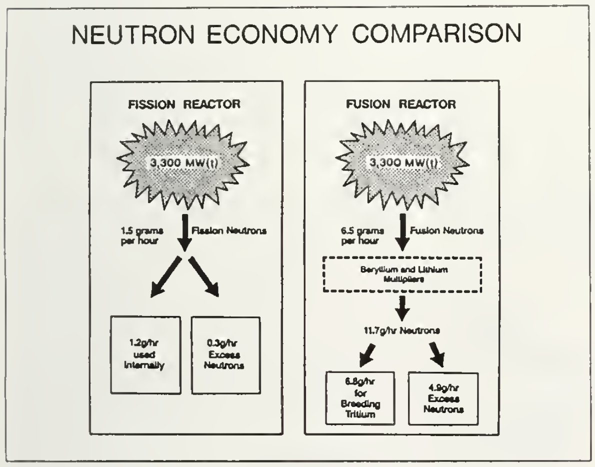


Figure 6

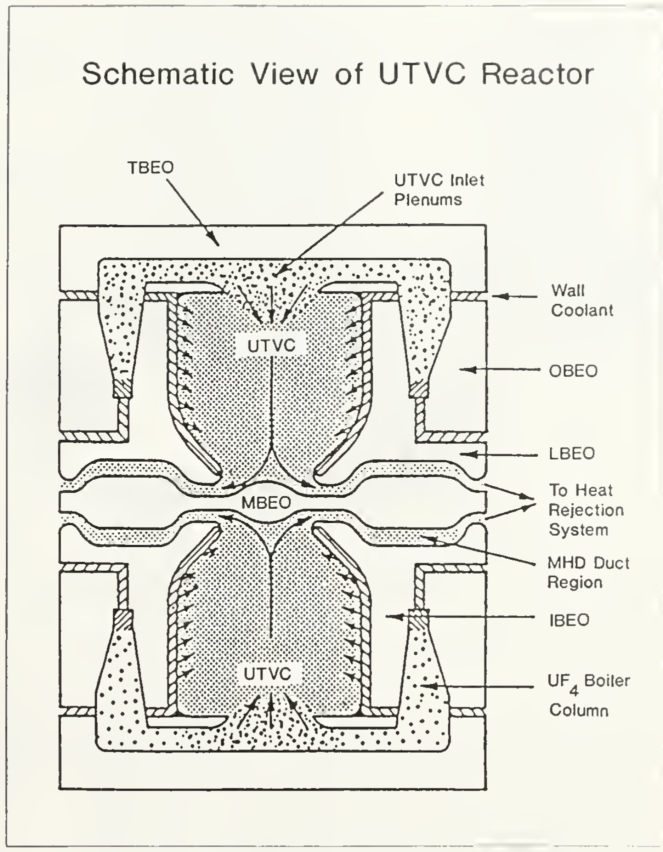


Figure 8

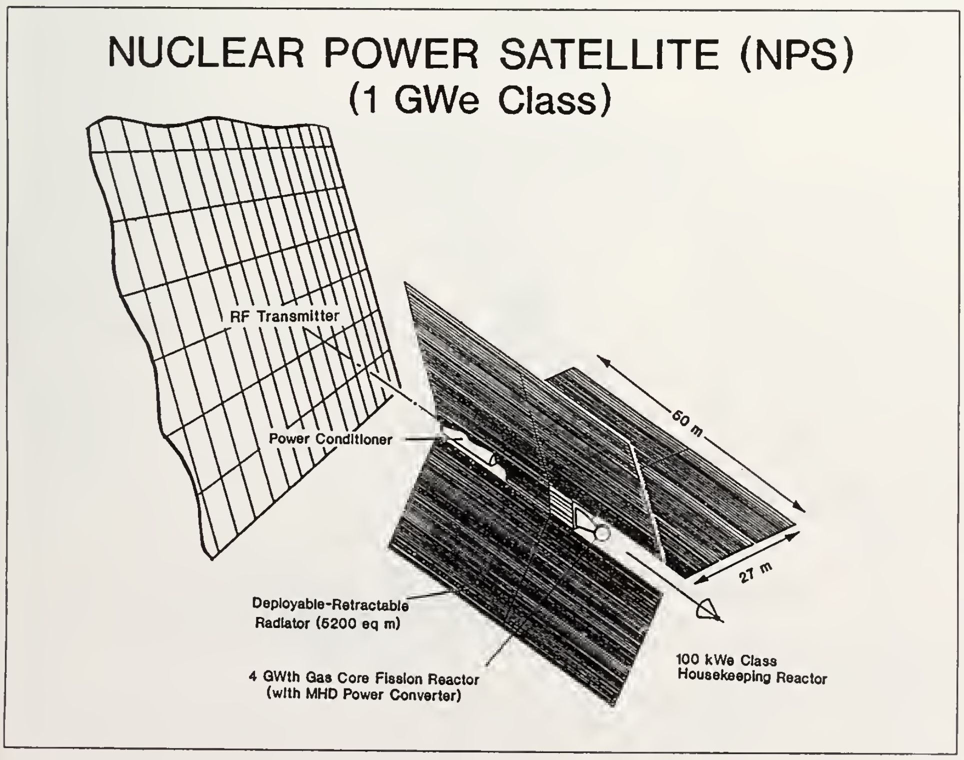


Figure 7

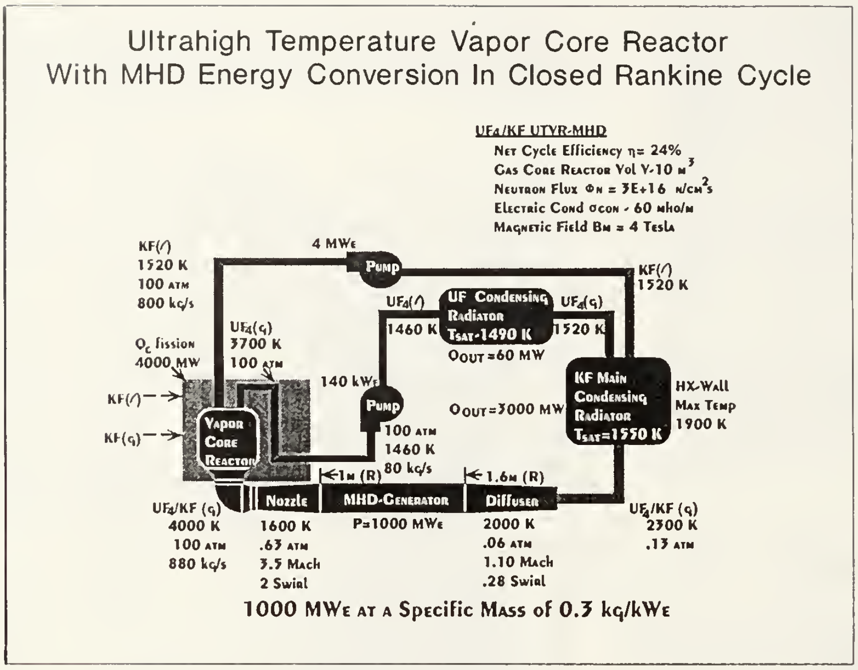


Figure 9

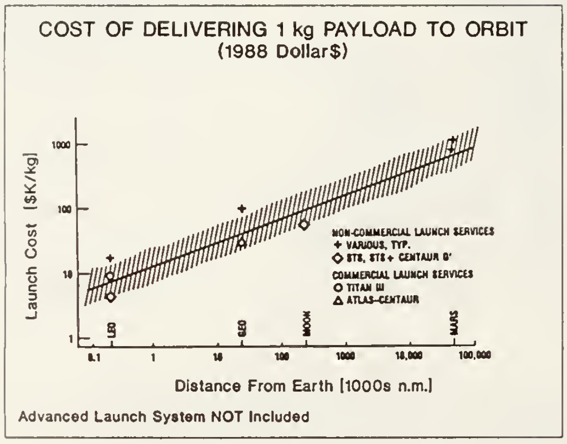


Figure 10

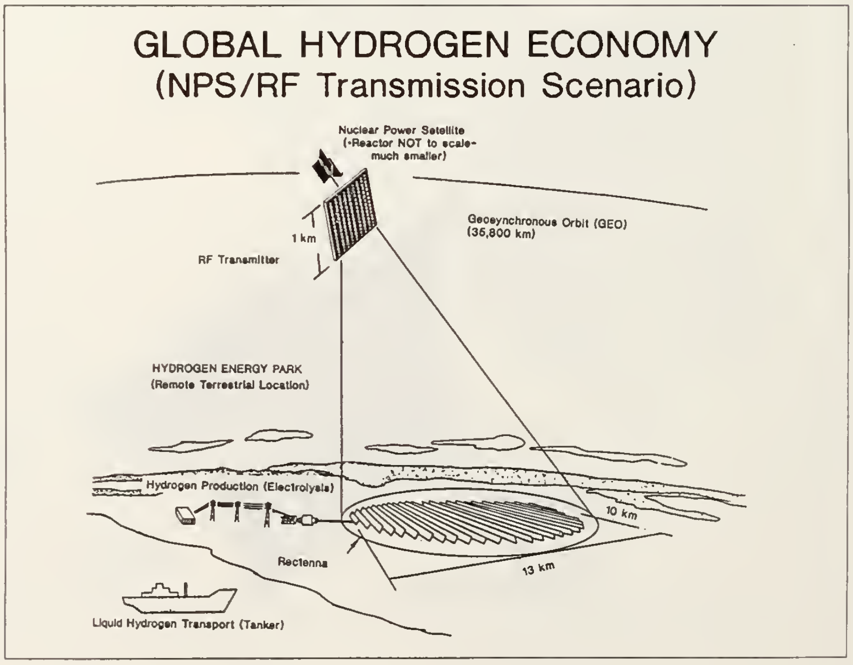


Figure 11

A2.4 Global space fusion energy

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N.N. SEMASHKO

SUMMARY

The report analysethe perspective of space thermonuclear power station.

RESUME

Ce rapport analyse les perspectives d'une centrale thermonucléaire dans l'espace.

The development of power engineering in the world, as the logistics analysys show, will gradually begin to face ever greater ecological restriction. The matter is that should the generation of various kinds of energy on Earth reach a level of 10 KW the global natural thermal equilibrium will be violated. Although till now the major source of energy on Earth is the Sun, wich emits 10 KW on it , the manking produces almost 10 KW and the power production growth goes on although the rate of gain gradually falls down. Scientists showed that the problem of overproduction of energy will become actual at the beginning of the next century (Fig.1).

One of the ways for its solving is to carry out the production of electric power into space, where the non used heat will be released into space, thus reducting the production of heat on Earth the latter receiving additional energy only in the form of the microwave radiation or laser.

Energy transmission can be carried out not only from a space electric station on Earth, but to other space ships, where the energy received can be used both in engines and in technological units.

A space electric station with the power of several millions of kilowatts can stay mainly on synchronous near-eath orbit. There are a number of project /2,3/ at the shape of such electric station, using solar o nuclear energy.

Solar and nuclear power plants of the spacecraft are already used in space /4,5/. A limiting factor of space solar electric station with fotoelectric energy transformation is in considerable dimension of solar-cell panels. With power 5000 MW and efficiency 20% their area will be about 20 km and specific mass 7 kg/KW. A space nuclear electric power station with the power of 5000 MW and efficiency 40% will have a cooler-emitter of the area 2.5 km and, besides, it will require a considerable radiation protection. The specific mass of such a station will be, perhaps, about 10 kg/KW. Progress has been achieved re- cently in approaches to the development of power of thermonuclear fusion. Space being the most suitable medium for thermonuclear power generation, this prob- lem is not studied yet. So, it is of interest to dwell on the use of thermo- nuclear power in space.

The amount of energy, released in plasma of the thermonuclear fuel, is pro- portional to particle concentration n and confinement time in the zone of reaction . The product of these values has a threshold value, wich is a criterion for obtaining the level of usefull energy and wich is dependent of the rate of fusion of various light nuclei. Fig.2 demonstrates dependences of criterion n on plasma temperature for three most widely discussed reactions /6/;

$$D+D \begin{cases} \longrightarrow T(1,01\ MeV) + p(3,03\ MeV) \\ \longrightarrow {}^3He(0,82\ MeV) + n(2,45\ MeV) \end{cases} \qquad (1)$$

$$D+T \longrightarrow {}^4He(3,52\ MeV) + n(14\ 06\ MeV) \qquad (2)$$

$$D+{}^3He \longrightarrow {}^4He(3,67\ MeV) + p(14,67\ MeV) \qquad (3)$$

It is clear that for reaction (2) the criterion n is minimum and is obtainable at more lower plasma temperature, i.e. it is easier to be carried out. For reactions (1) and (3) this value is much highter. However, by fusion of helium from deuteron and tritium the greater fraction of energy is caried away by neutror and this energy can be converted into electricity only in thermal cyc- lies. Reaction (2) is also often considered as a basis of hybrid reactors - with a fasible material in the blanket. The products of reactions (1) and (3) are mainly charded particles, the energy of which can be directly converted into electricity with high efficiency. These two reaction can be also used simultaneously in so-called catclyzed D+D cycle:

$$3D \longrightarrow p + {}^4He + n + 21,6\ MeV \qquad (4)$$

About 75% of energy in this case is carried by charged particles /7/, that is why the thermal cycle of energy conversion ceised to play a dominating role.

It is evident that for space power plants the direct conversion is more promising when a

non-neutron reaction $D+{}^3He$ is used in its pure form or with minimum effect of the catalyzed D + D cycle. System with such fuel cycles will be characterized by high efficiency and with no rotating parts and heavy radiation protection, that providing their low specific mass, minimum cost and high operation reliability.

Consider in detail a possible scheme of the power plant with thermonuclear reactor (Fig.3), in which the reaction $D+{}^3He$ is realized. One of the most promising method for plasma heating till temperature of several hundereds of KeV is the injection of high energy fluxes of atoms of thermonuclear fuel /8/. Since the injector will consume the greater psrt of power of a thermonuclear electric power station, it is necessary to increase its operation efficiency. For this we offer to use so-called recuperators , in which the flux of non-recharded ions decelerates by the electric field; the kinetic energy of the flux is converted into electric energy and returns into the external circuit of ion accelerator.

At present the models of such recuperators showed high efficiency of deceleration (Fig.4), reaching 70-80% /9/. No doubt, that their parameters will be further improved.

Recuperators will become the major part of the system for converting the kinetic energy of charged particles, escaping from the thermonuclear reactor. Though for the development of such devices we need serious studies of scientific and technical problem, one can at once notice their large advantages, conditioned by the absence of thermal cycle, the efficiency of which is confined with the Carnot cycle.

The total efficiency of a thermonuclear electric power plant with direct conversion, the scheme of which is shown on Fig.3, is determined from power balance:

$$N_n = \eta_p(\alpha N_T + N_u) - \frac{N_u}{\eta_u} + \eta_p(1+\eta_u)N_u \quad ,$$

where Nn isuseful power, N is thermonuclear power, Nu is the injection power, η_u and η_p is the effiency of the injector and recuperator, α is a fraction of the thermonuclear power, falling at charger particles (as is shown in /10/, which 30% content of He in the heat mixture α= 0.94).

The useful power-thermonuclear power ratio gives us the total efficiency η_o:

$$\eta_o = (\alpha + \frac{1}{Q})\eta_p - \frac{1}{Q}\eta_u + (1-\eta_u)\frac{\eta_p}{Q} \quad ,$$

where Q is the parameter, characterizing a specific thermonuclear energy release (per unit power injected).

Dependence of η_o on the parameter is shown on Fig.5 for actually obtainable efficiency of injection and direct conversion. It is seen that the value of total efficiency 0.7 is achieved at Q = 1. Such level of parameter Q can be provided with the use of reaction $D+{}^3He$ in a number of systems with magnetic confinement (as, e.g. in /7/).

Consider the characteristic of a space thermonuclear electric power plant. Thermonuclear reactor and other system of the station are, perhaps, convenient to be arranged in the constraction of extended form with a microwave aerial or with a laser and a cooler-emitter at the terminals. Such a "dumb-bells" form of the station will make its stabilization on orbit much easier (Fig.6).

With the power of the station of some qW the diameter of transmitting microwave aerialwill be about 1 km. n /11/ there are given weight characteristic of microwave-system; specific mass 0.25 kg/kW, efficiency of a microwave- system can reach 70%.

It is seen from here that the aerial will not greatly affect the mass of a space electric power plant of any type.

The total dimension of a space thermonuclear power plant, as well as of a space nuclear electric power plant, will be determined by the size of an aerial and a cooler-emitter - at η_o= 0 the area of a cooler will be 1 km . The mass of a thermonuclear reactor with direct conversion is determined mainly by the mass of a superconducting magnetic system. In /4/ there are given values of specific mass of a space thermonuclear reactor for spacecraft, which in the absence of typically ground systems will make up about 2 kg/kW. Taking into account various aditional system of the station (cryogenic, separation of fuel components, etc.), we are a preliminary and, perhaps, slightly overrated value of the specific mass of a space thermonuclear power plant - 5 kg/kW.

In a number of works (e.g. /13/) a const analysis is given for differnt members of a thermonclear reactor with direct conversion. Assuming that costs on reactor's equipment make up the major part of total cost of a space thermonuclear power plant, we get a value of station's specific cost 200 dol./kW. Evidently, in future all costs will grow.

It is seen that even in choosing nonoptimal parameters of a space thermo nuclear power plant it is much more profitable than that of a space solar elec- tric power stations. Charateristics of these stations are given in table I, values of which can be considered as particularly approximate.

Table I.

Parameters	Space solar electric power plant	Space nuclear electric power plant	Space thermonuclear electric power plant
Power emitted, MW	5000	5000	5000
Efficiency of a power plant	0.2	0.4	0.7
Efficiency of a microwave-system	0.7	0.7	0.7
Primary power, MW	35.7	17.8	10.2
Dimension of a station, km	25.5	2.6	1.0
Specific mass, kg/kW	7	10	5
Total mass, t	35000	50000	25000
Specific cost of equipment, dol./kW	300	250	200
Total cost of equipment, bil.dol.	1.5	1.25	1.0
Cost of delivery at specific 100 dol./kg, bil dol.	3.5	5.0	2.5
Total cost of a station, bil.dol.	5.0	6.25	3.5
Cost of production, 1 dol./kW	1000	1250	700
Cost of electric power at 10-year operation, dol./kWh	0.01	0.0125	0.007
Relative cost of stations	1.43	1.78	1
Relative cost of stations by K.Erike /3/	1.24	1.2	1

The creation in orbit of such firs massive construction is possible only in large freight traffic from Earth into space, which is very small from economical point of viev. Should we produce power comparable with that on Earth, this process, as calculations show, will take several thousand of years, i.e. it is actually not acceptable.

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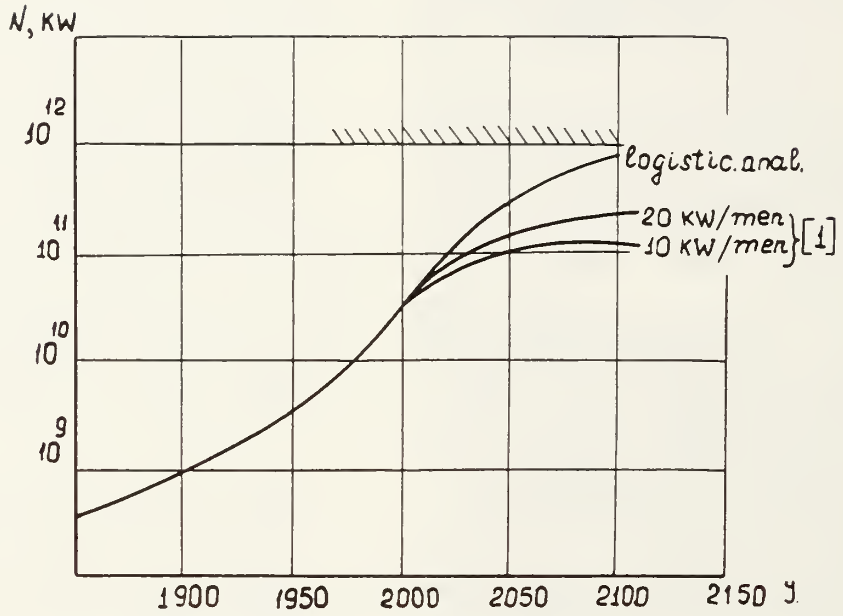
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Fig. 1

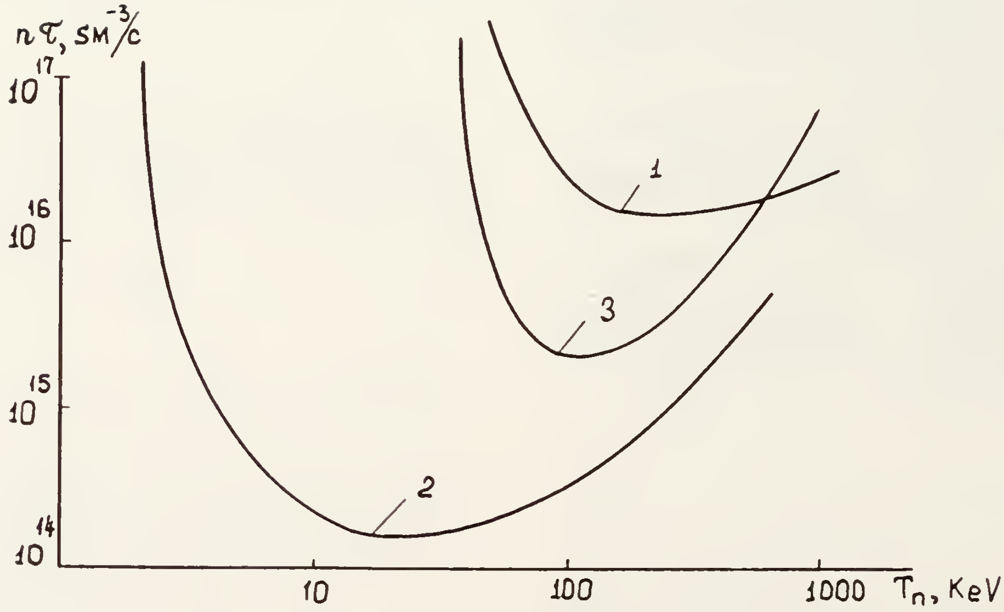
$n\tau$, sm^{-3}/c
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Fig. 2

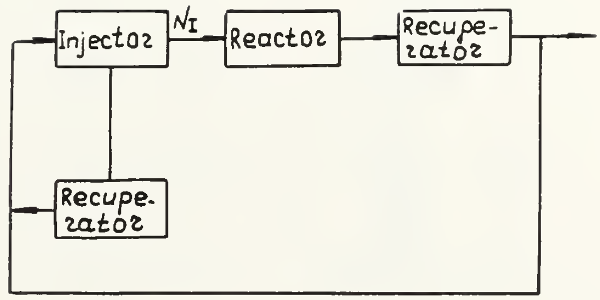
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Fig. 3

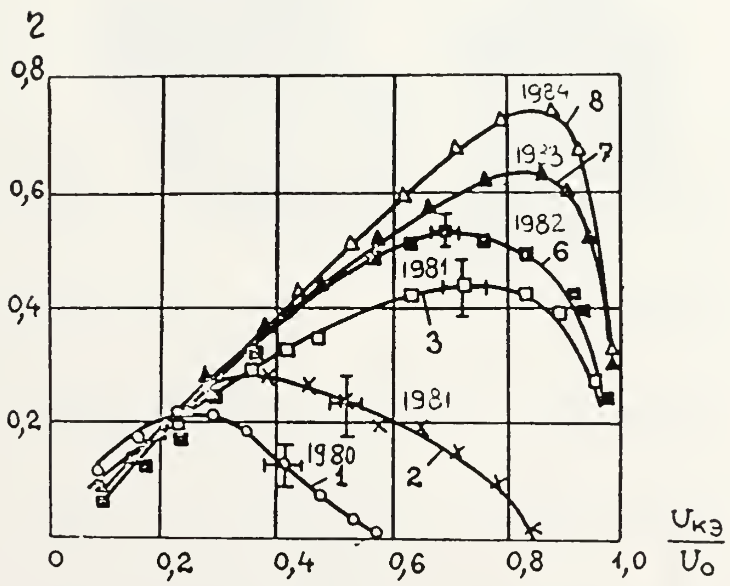
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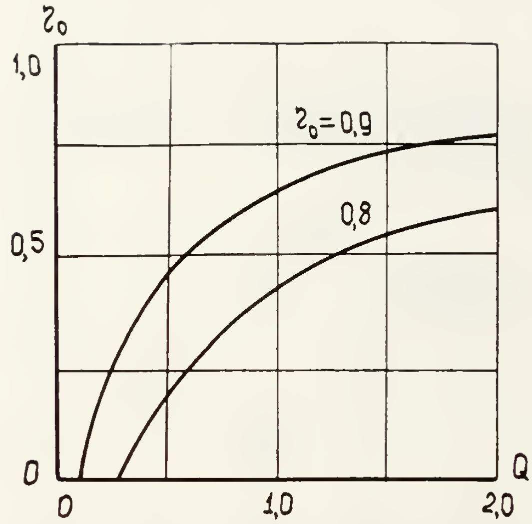
Fig. 4



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$\eta_0 = 0{,}9$
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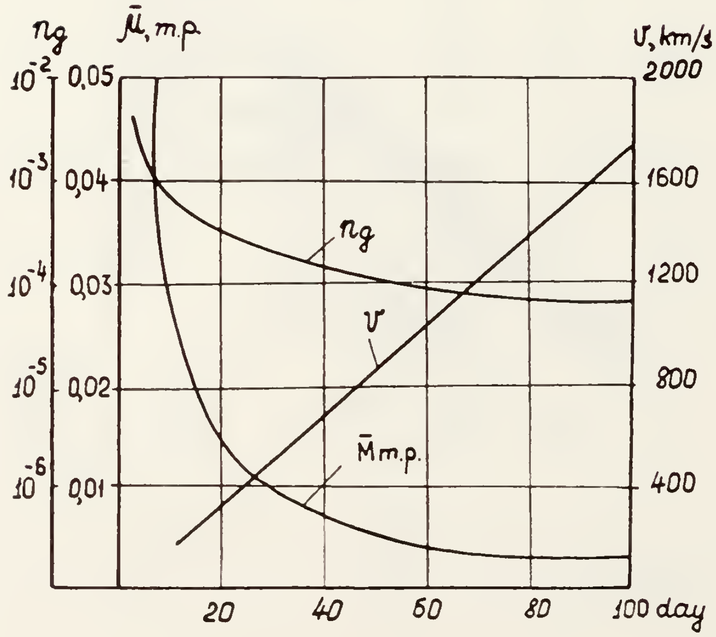
Fig 5



ng
$\bar{\mu}$, m.p
v, km/s
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10^{-3}
10^{-4}
10^{-5}
10^{-6}
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0,04
0,03
0,02
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2000
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1200
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400
ng
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40
60
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100 day

Fig 7

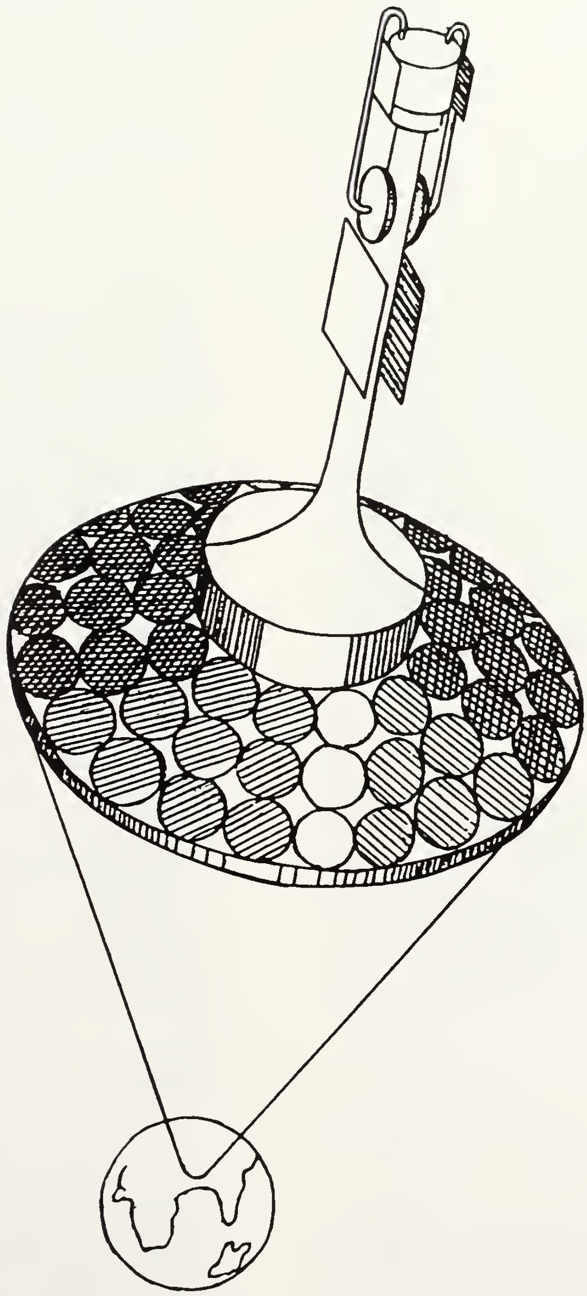

Fig 6

A2.5 A method for utilities to assess the SPS commercially

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Abstract

Most of the literature on satellite solar power stations (SPS) has considered the combined satellite-rectenna unit as a means of generating continuous power. This paper shows that by considering the rectenna as an independent facility owned and operated by a utility, the utility could use their existing expertise to estimate how much they would be prepared to pay for supplies of microwave power from space, thereby providing clear cost targ-ets for space engineering companies. In addition a range of more flexible and more profitable modes of operation for the SPS can be analysed, including provision of daytime power, provision of power to a rectenna from more than one satellite, and coordinated operation of a system of several satellites.

Résumé

Dans la plupart des études sur SPS on traite la combinaison satellite-"rectenna" comme une unité pour la génération continue de puissance. Dans cet article on montre que si l'on traite le "rectenna" comme une centrale indépendante qu'opère une compagnie productrice d'électricité, celle-ci peut estimer combien elle pourrait payer les transmissions de puissance microonde de l'espace, ce qui donnera des buts clairs commerciaux pour les compagnies de technologie spatiale. En plus, plusieurs modes d'emploi du SPS plus flexibles et plus rentables peuvent être analysés, y compris la provision de puissance pendant la journée, la provision de puissance de plusieurs satellites à un seul "rectenna" et l'opération coordonnée d'un système de plusieurs satellites.

Introduction

For the SPS project, as for any new commercial venture, the concerns of potential customers are of primary importance. The customers for the SPS will be the major electric utilities of the world, and it is therefore essential to consider the SPS from their point of view.

The concerns of electric utilities centre, in turn, on the needs of their customers, and in particular on the pattern of demand for electricity. This is not constant, but fluctuates according to a number of regular patterns. First there is a daily cycle, whereby for most utilities the daytime level of demand lasts for some 16 hours and then falls by some 50% for the 8 hours of night-time. There is also an annual cycle, which for some utilities shows an average winter demand approximately 100% higher than the summer average; for other utilities the summer average is higher than the winter. There are also weekly cycles and short-term surges at peak demand periods during the day.

In order to supply this power, utilities operate electricity generating capacity of different types, some providing continuous "baseload" power, some

providing daytime power, and other capacity providing short-term "peak" supplies. The marginal cost per kilowatt-hour from each of these sources is different, generally being lowest for baseload power and highest for short-term supplies.

Most SPS studies have assumed that, because of the SPS's high capital cost and the corresponding need to maximise its usage, each satellite would be used to transmit "baseload" power more or less continuously to a single rectenna. However, this assumption overlooks the fact that the value of electric power is not constant but varies during the day and over the year.

Moreover, the SPS has technical capabilities that make a system of satellites and rectennas capable of more flexible modes of operation which are of much greater value to electricity supply companies, and therefore potentially more profitable to satellite operators. Supplying baseload power narrows the scope for the SPS operation, and ignores a major part of the system's potential value. It also sets the most demanding cost targets for the SPS, since it would be in competition with other base-load plant with the lowest operating costs.

Alternative Assessment Method

An important feature of the SPS project is that it involves two distinct industries, space engineering and electricity supply, whose fields of expertise are both essential to the project, but very different. One possibility for overcoming this difficulty is to treat the ground segment and the space segment as two separate investment projects: Thus a utility would construct, own and operate a rectenna integrated into its power supply grid but a different organisation would own the satellite and be responsible for its operation and maintenance. The utility would then purchase microwave 'fuel' from the satellite company.

Such a division of the overall system would have considerable similarities to the operation of international satellite telecommunications: INTELSAT commissions, purchases and operates telecommunications satellites, and leases channels to its users who construct, operate and control their own earth terminals. It would also be similar to the new, non-integrated structure of the electricity sector in the UK, where a number of local distribution companies purchase electricity from a range of generators.

Cost targets for the space segment could be found as follows. Utilities would estimate the cost to them of installing and operating a rectenna in their grid, and would calculate what additional price it would be economic for them to pay for microwave 'fuel' under different conditions. This would then provide the targets for the satellite company's costs.

The evaluation of the SPS proposal would be much enhanced by the direct involvement of utilities. However, the prospect of financing an extremely large capital investment in a field with which they are unfamiliar is not attractive to utilities. One advantage of the approach outlined above is that the technological and economic uncertainties concerning the rectenna are much less than those relating to the space segment. Most of the major technologies involved in the rectenna lie within utilities' existing fields of expertise, and so they could become independently involved from a very early stage.

Rectenna Cost Contribution

Every rectenna would, to a considerable extent, be unique both in the civil engineering requirements of the site and in its electrical connections to the existing grid. However, the method proposed above can be demonstrated in a simplified form. The annual cost, C_r, to a utility of operating a rectenna can be expressed as:

$$C_r = C_{cap} + C_{O\&M} + C_{fuel} \quad (1)$$

Where C_{cap} = annual capital cost

$C_{O\&M}$ = operation and maintenance costs

C_{fuel} = microwave 'fuel' cost.

These cost elements can be broken down further:

C_{cap} = (capital recovery factor)x(rectenna initial capital cost)

$C_{O\&M}$ = direct operating costs + repair & maintenance costs.

The capital recovery factor depends on the required rate of return on assets and their lifetime (see Table 1), and the rectenna capital cost is the sum of the site acquisition and preparation cost, the support structure cost, the receiving antenna cost, the power conditioning and grid interface cost and additional storage cost.

required rate of return for UK nationalised industries) and a rectenna lifetime of 30 years. The operation and maintenance costs include a number of elements. The figure of 3% per annum of capital cost assumed here is that used by Cottrill (2) for other renewable energy sources. Table 2 shows the cost of operating a rectenna on these assumptions.

Microwave "fuel" price

In 1988/89 the average operating cost for the CEGB's power stations was 3.53p/kWh (3). Future power stations may be of the combined cycle gas turbine type or advanced coal combustion technologies. James Capel (8) estimate the variable operating costs of such plant to be in the range 1.3-1.5 p/KWh, which implies an operating cost of around 3.0 p/kWh.

Project lifetime	Interest rate 15%	Interest rate 10%	Interest rate 5%
20 years	16.0	11.7	8.0
25 years	15.5	11.0	7.1
30 years	15.2	10.6	6.5
35 years	15.1	10.4	6.1
40 years	15.1	10.2	5.8

Table 1: Annual capital recovery factor as a percentage of initial capital cost

Using equation (1) we can use cost estimates from the literature in order to calculate what would be an economic 'fuel' cost. Denman et al (1) estimated the rectenna capital cost at \$3000m in 1977\$, which converts to approximately £600/kw (assuming US inflation of 5%/year since then, and an exchange rate of \$1.90 : £1). The correct rate of return on capital is a matter of debate, and so we consider the two cases of 5% and 10% (which are the past and present values of the

Hence if the SPS were to be competitive with modern coal-fired plant, the utility could pay up to 1.96p/kWh (ie 3.00-1.04) for microwave 'fuel' if the rectenna capital cost were £600/kW, the discount rate 10% and the load factor 90%. Alternatively, at 70% load factor, £400/kW capital cost, and 5% discount rate, the utility could pay 2.38p/kWh.

For the SPS to be economically viable its overall cost of electricity should be competitive with

Initial Capital Cost	$C_{O\&M}$ Annual O&M Cost	C_{cap} Annual Capital Cost disc. rate		Unit Cost 90% load factor		Unit Cost 70% load factor	
		a) 10%	b) 5%	a)	b)	a)	b)
£/kW	£/kW	£/kW		p/kWh		p/kWh	
400	12	42.4	26.0	0.69	0.48	0.89	0.62
600	18	63.6	39.0	1.04	0.72	1.33	0.93
800	24	84.8	52.0	1.38	0.96	1.78	1.24

Table 2: Rectenna cost contribution to SPS power cost for different capital costs, discount rates and load factors

the alternatives. However, the criterion for being suitable to provide baseload power is that its <u>operating</u> costs should be competitive with other baseload plant - which is a more stringent condition. In the UK, nuclear power stations have the lowest running costs; the estimated generation cost for a new PWR power station is given by Jones & Woite as 0.98 p/kWh (1989 prices), (9). Table 3 shows the maximum price which could be paid for microwave 'fuel' if this target were to be met by a rectenna. It is thus possible that the SPS could become competitive as an energy source but not be high enough in a utility's merit order to provide baseload power.

transmit microwave power to other rectennas some distance away around the globe, thereby acting as a peakload power source at several locations.

<u>Value of flexibility</u>

Following this approach, it can be seen that significant economic benefits would arise if SPS systems were designed

1 to allow a satellite to switch some or all of its transmitted power between two or more "rectennas" according to the pattern of demand on the rectennas, and
2 to allow rectennas to receive microwave power from one or more satellites simultaneously.

TABLE 3 <u>Maximum microwave 'fuel' price for base load operation</u>

Capital Cost	Operating Cost		Target Cost	Maximum Fuel Cost	
£/KW	90% p/KWh	70% p/KWh	p/KWh	90% p/KWh	70% p/KWh
400	0.15	0.20	0.98	0.83	0.78
600	0.23	0.29	0.98	0.75	0.69
800	0.30	0.40	0.98	0.68	0.58

In this case the expected flexibility of the power output of the SPS could be valuable in allowing the rectenna to perform two-shift operations. Although the rectenna would not achieve a high load factor, the satellite supplying it could still do so if it were to

The combination of these enhancements would permit the achievement of a high load factor on the satellite (which represents some 80% of the total system cost) while utilising the rectennas to which it delivered power at lower load factors for the provision of daytime and peak

load power, for which the cost to utilities is substantially more than for base-load power. That is, since the capital costs of both satellite and rectenna dominate their operating costs, the contribution of both segments to the cost of SPS power is dependent on the load factors at which they are operated, the space segment being substantially more important. Thus, provided that the load factor on the space segment can be kept high by delivering power to more than one rectenna in succession during the day, rectennas could be operated profitably even at relatively low load factors.

Figure 1 illustrates the additional flexibility of rectenna operation that this permits: A particular system might not be competitive as a baseload power source even if both satellite and rectenna were operated at the maximum load factor of 0.9, and it might not be economic if operated with a load factor of only 0.67 (typical for daytime demand) on both satellite and rectenna. The system could nevertheless provide daytime power profitably with a load factor on the rectenna as low as 0.6 if the satellite load factor was 0.9. The shaded area illustrates the range of load factors over which the system could be both profitable and competitive for supplying daytime power.

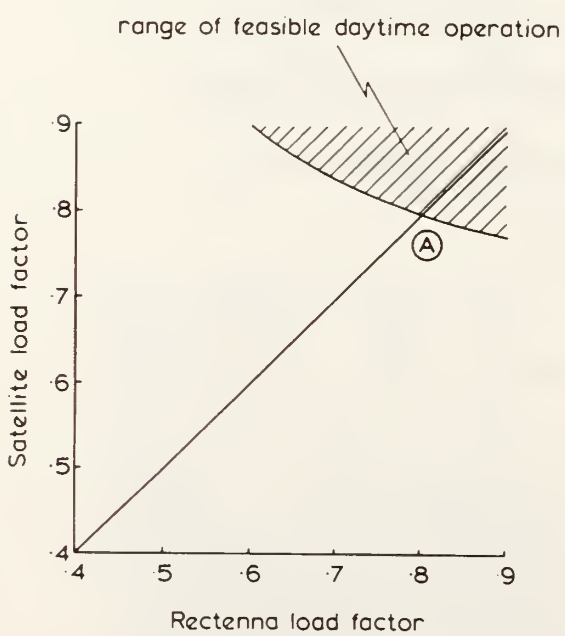

Figure 1: Scope for provision of daytime power through separate operation of satellite and rectenna

Thus in a given case, an SPS might be uncompetitive as a base-load power source, but be attractive as a source of daytime and peak power. In order to exploit this potential fully, a mature SPS system should not comprise equal numbers of satellites and rectennas but should contain more rectennas than satellites, at least some of which should provide power intermittently to several different rectennas.

The operation of rectennas at low load factors would be more attractive the lower was the capital cost per kilowatt of the rectenna. The potential benefits of more flexible power supply therefore constitute an additional incentive to design low cost-per-kilowatt rectennas. A promising means of reducing the rectenna cost per kilowatt would be to use rectennas designed to receive power from two or more satellites simultaneously (4). The cost of a rectenna capable of handling the output of two satellites would be between 132% and 145% of the cost of a single capacity rectenna (5). Consequently a rectenna uprated to double its initial capacity would be economical to operate at lower load factors.

Flexible SPS Operation

There are several different ways in which the potential flexibility of a system of SPSs could be utilised to follow the loads at different rectenna sites as they vary over the time of day or year:

Supply of Daytime Power by a satellite to more than one rectenna

A satellite supplying daytime power to a rectenna would be unloaded between the hours of approximately 10 p.m. and 6 a.m. local time at the rectenna. It would therefore be free to transmit power to other rectennas during this period each day. Transmission to other rectennas sited in

different time zones from the primary rectenna would permit the transmission of daytime power to these rectennas during the night-time load period of the primary rectenna.

Time zones are typically 15 degrees of longitude in East-West extent, and consequently, assuming similar daily load curves, rectennas separated by more than 15 degrees of longitude could differ by one or two hours in the timing of their load curves, while rectennas separated by more than 30 degrees could differ by two or three hours. Thus a satellite at the same longitude as its primary rectenna might deliver three hours of daytime power to a rectenna some 30 degrees West of the primary rectenna from 7 p.m. to 10 p.m. at the rectenna (ie 10 p.m. to 1 a.m. local time at the satellite) plus three hours daytime power to a rectenna some 30 degrees East of the primary rectenna from 6 a.m. to 9 a.m. local time at the rectenna (ie 3a.m. to 6 a.m. local time at the satellite) in addition to supplying full daytime power to the primary rectenna from 6 a.m. to 10 p.m., as illustrated in Figure 2.

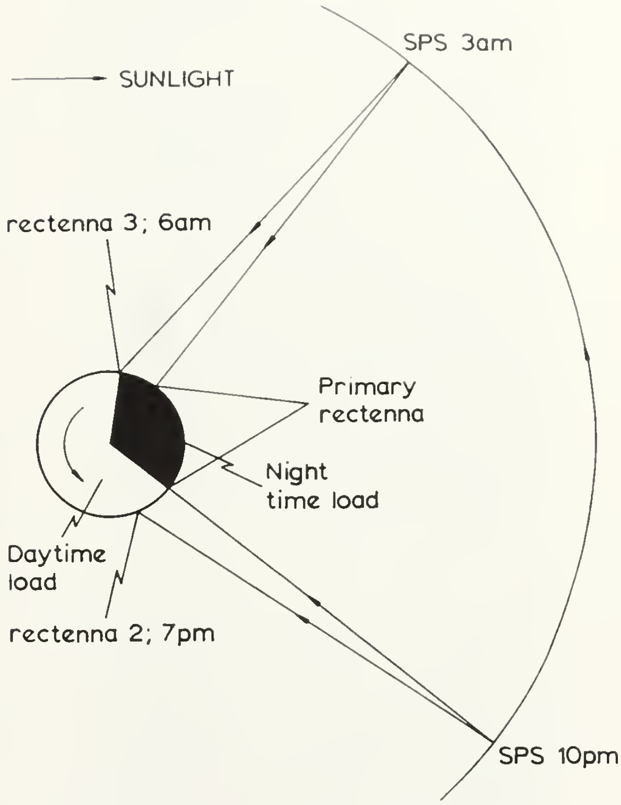

Figure 2: SPS operation for full daytime provision at primary rectenna, plus daytime fuel saving at two secondary rectennas

When power is transmitted from a satellite to a rectenna with a longitude offset from the satellite, the area over which the microwave beam is spread at the ground increases. For a longitude offset of 30 degrees the area of the rectenna increases by some 50% (depending on the latitude of the rectenna) over the area of a rectenna delivering equal power with zero longitude offset. This would increase the cost of the rectenna by some 25% (5).

Following this schedule, the satellite would thus save both plant capacity and fuel costs for the full daytime load period of the utility operating the primary rectenna, as well as providing three hours' daytime fuel saving for each of the other two utilities. The load factor on the satellite would of the order of 0.9, which is the target for the SPS space segment (6), while that on the rectennas would be 0.67, 0.125 and 0.125 respectively. In order to be economic for the utilities operating the secondary rectennas, these would each have to receive power from some other satellite for some part of the day in order to increase their overall load factors. If, for instance, each of the secondary rectennas had similar arrangements with two other satellites, the load factors could reach 0.37, which might be economic for a rectenna uprated to receive power from multiple satellites (5).

<u>Back-up Supplies and Grid Interlinking</u>

The antenna design that has to date been considered most appropriate for the SPS is a phased-array antenna. Such systems have the technical capability to alter the direction of the transmitted microwave beam in a very short time: Radar transmitters with power

outputs of the order of 100 kW currently switch their beam direction in time periods of less than 1 millisecond. Consequently, even allowing for the very much larger power output of the SPS it should be technically possible to switch the direction of the power transmission from one rectenna to another within a few seconds. In practice, constraints on doing this are likely to arise within the ground segment of the system, both in the maximum rate of change of power flow than can be tolerated within an electricity grid, and in the maximum rate of change of load that is experienced by utilities.

The most rapid changes in power flows that occur in a typical grid result from the sudden loss of the output of a power station. Hence, provided that the arrangement was economically attractive, an SPS might be used to provide periods of standby power supply to one or more utility grids, covering both loss of output and rapid increases in load. If the grid to which an SPS was currently delivering power contained sufficient storage and/or standby capacity to replace the SPS output at very short notice, the SPS could at the same time provide backup power to another grid, enabling several grids to share their standby and reserve capacity. With several SPSs delivering power to a number of different grids, this flexibility could substitute in part for the use of long distance transmission cables between the grids.

The potential for short-term flexibility of power delivery could be exploited most fully if satellites had two transmitting antennas with the capability to transmit two power beams simultaneously of which the power levels could be varied smoothly. Technically it would be possible to vary the output of an SPS continuously, but whenever power was being delivered at less than the maximum rate possible, some of the system capacity would be being wasted. The use of a satellite with two antennas, of which the combined capacities exceeded the capacity of the satellite, would enable the power output of the two antennas to be adjusted inversely. In this way the load factor on the satellite could be kept at its maximum, and the power delivered to the two rectennas be adjusted to match best the requirements of the two utilities.

Figure 3 illustrates a possible pattern for sharing of the output of an 8 GW satellite between two 5 GW antennas. (An alternative means of transmitting two microwave beams from a single satellite has been proposed by Arndt and Kerwin (7) who have described single antennas capable of transmitting two and four microwave beams at an overall cost of power very similar to that of single beam antennas. However, the efficiency of power transmission falls off as the separation between rectennas increases, which would greatly restrict the

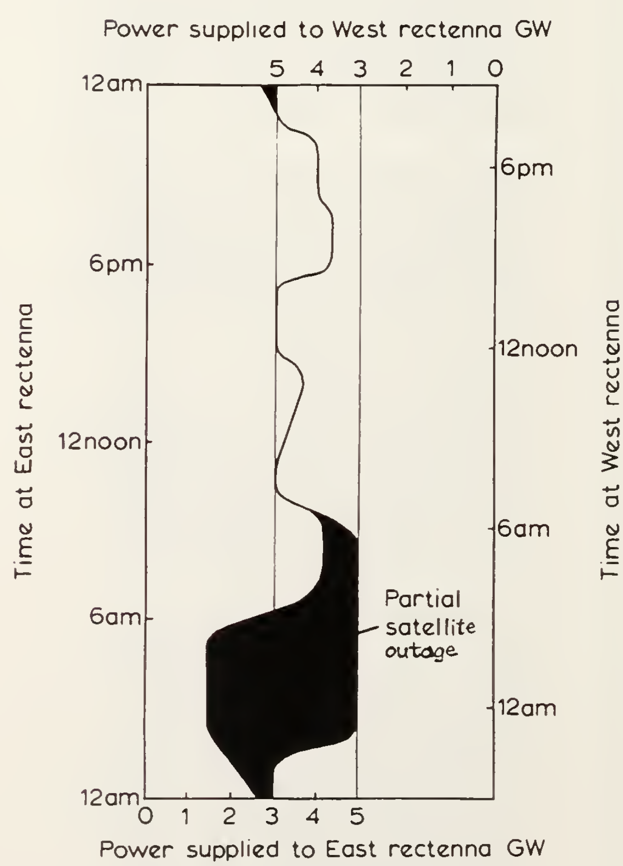

Figure 3: Pattern of sharing output of 8 GW satellite between two 5 GW antennas

scope for long distance power switching). The cost per kilowatt of an 8 GW satellite with two 5 GW transmitting antennas would be some 12% more than the cost of a 5 GW system (5). This margin might be compensated by the greater flexibility of delivery and the potential for somewhat higher satellite load factors due to the possibility of shutting down one antenna for maintenance work while maintaining more than 60% of power output from the other antenna.

Seasonal SPS Capacity Sharing

A major opportunity for sharing the output of a satellite between two rectennas results from the fact that the periods of maximum demand on different electricity grids arise during different seasons of the year. (For instance, the maximum demand on some American electricity grids arises during the Summer when the demand for cooling is highest, while in Northern Europe the maximum demand arises during the Winter). Consequently a single satellite could be operated in such a way as to supply baseload power to one rectenna during the Winter months and to supply the same to another rectenna during the Summer. In this way each rectenna would achieve a load factor of approximately 0.45 (ie 50% of 0.9). If each rectenna also received six hours of daytime fuel-saving supplies for approximately half the year, they would achieve overall load factors of 0.57.

Such a Winter/Summer peak delivery pattern would make a convenient match with the fact that for three weeks either side of the equinoxes (Mar 21st and Sept 23rd) geostationary satellites are eclipsed for a few minutes around midnight. Thus, by concentrating some of the planned outages for necessary maintenance into these periods, an SPS would be able to achieve higher load factors during the months of maximum demand. This potential for sharing capacity on a seasonal basis between two widely separated utility grids is a capability that is unique to the SPS.

Coordinated Operation of a Global SPS System

As the number of satellites and rectennas in a global system increased, the average longitude offset between them would decrease, and the scope for economising on satellite capacity through coordinated operation of satellites would increase. Such arrangements would be facilitated by the formation of long-term supply agreements between several different utilities. A computer model has been used to estimate the scale of savings that might be achievable in practice through the coordinated switching of power between several satellites and rectennas.

Optimal Operation of SPS Systems

In order to study the potential benefits of switching power supplied from satellites between several rectennas according to the changing pattern of demand during the day, a system of sixteen rectennas was selected, sited at major population centres around the world. For this exercise, assumptions were made about demands to be served at peak and off-peak times (see Table 4).

A critical parameter in determining the relative profitability of supplying peak or base load power from an SPS is the ratio of the marginal costs of power at peak and base load periods. We have not attempted to forecast the marginal costs at the various locations next century, but have merely taken a ratio of 2:1 as representative. On this assumption, if satellites were used to provide power only during the daytime period, the duration of which is commonly sixteen hours, they would earn 33% more than if used to provide base load power. Similarly, if a set of satellites were used to supply equal amounts of base and peak power, average satellite revenues per kWh would be 16.5% more than if supplying only base load demand.

Table 4: Rectenna Sites.

Demand Centre	Demands Peak	(GW) Off-Peak	Electricity Supply Costs (London = 100)
London	12	6	100
Amsterdam	12	6	100
Genoa	10	5	100
Istanbul	10	5	120
Bombay	10	5	120
Bangkok	10	5	120
Hong Kong	12	6	120
Shanghai	12	6	120
Osaka	12	6	100
Tokyo	12	6	100
Sydney	10	5	90
Los Angeles	12	6	90
Chicago	12	6	90
Washington	12	6	90
New York	12	6	90
Sao Paolo	10	5	110

If the capacity of SPSs to switch the direction of their microwave beams is to be fully exploited, less satellite capacity should be employed than the total rectenna capacity. A set of thirteen satellites, with capacities ranging from 8.4 GW to 12.4 GW, with a total capacity of 130 GW, were allocated positions in geostationary orbit, to serve the sixteen rectennas with total peak demands of 180 GW. Costs at other demand centres in Table 4 are assumed to vary plus or minus 20% from the U.K.

A linear programming model was formulated to determine the allocation of power from satellites to rectennas in order to maximise the total revenue earned by the satellites. It was assumed that the revenue to a satellite would be the same as the marginal cost to a utility of alternative supply. The formulation is as follows:

Maximise revenue Z = $c_{jt}\ X_{ijt}$

where C_{jt} = the marginal supply cost of 1 GWh at rectenna j in time period t; and X_{ijt} = power received at rectenna j, from satellite i, time period t;

subject to:

(1) $X_{ijt} \leqslant D_{jt}$ j = 1,2,....16

where D_{jt} = demand at rectenna j, in time period t; and

(2) $P_{ij}\ X_{ijt} \leqslant S_i$ i = 1,2,.....13

where P_{ij} = ratio of power transmitted from satellite i to power received at rectenna j; and S_i = capacity of satellite i.

The need for the P_{ij} factors exists since more power must be transmitted from the satellite than is received at the rectenna, and as the longitude offset between a satellite and rectenna increases, the area of the "footprint" of the microwave beam on the ground increases. (In practice it would be possible to receive the entire beam, at the expense of increasing the area of the rectenna concerned). Satellites were permitted to deliver power to rectennas with longitude offsets of up to approximately 40 degrees.

The above L.P. was solved for four typical hours in a 24 hour cycle (01.00, 07.00, 13.00 and 19.00 GMT), to give an optimal switching pattern for the microwave beams. The model solution achieved a 15% average revenue increase over the 1:1 daytime only case, and a 53% increase over the 1:1 baseload case. The average satellite load factor achieved was 0.80, compared to 0.67 in the corresponding 1:1 case. Average rectenna load factors were 0.53, compared to 0.67 in the 1:1 case.

Although this model was very simplified, the potential for optimising the operation of a flexible system is clearly substantial. A range of more complex L.P. models can also be formulated with various objectives, such as to select the optimal sizes and optimal locations of satellites, as well as the optimal pattern of power transmission over typical 24 hour cycles

CONCLUSION

It could be very valuable if electric utilities were to contribute to the appraisal of the SPS to a greater extent than they have in the past. A particularly valuable form that such a contribution could take would be for one or more utilities to evaluate the cost of designing and constructing a rectenna linked into their distribution grid, and of operating it as one component of their power station "mix". This would enable utilities to calculate the value which they would place on supplies of microwave "fuel", and hence what price it would be profitable for them to pay for deliveries of microwave "fuel" to their rectenna. This would create a market for microwave power from space, and set cost targets for the designers of the SPS space segment. Space engineering companies would then compete to supply microwave power of the appropriate technical specification on the most competitive terms.

The potential to transmit large amounts of power across very long distances at short notice is a unique feature of the SPS. The exploitation of this capability would permit more profitable operation of a system of SPS units than the provision of base load power, by achieving high load factors on the space segment while delivering daytime power from the ground stations linked to local utility grids. Further studies aimed at determining and assessing in more detail the satellite and ground system specifications necessary to achieve these capabilities would therefore be desirable.

Decoupling the load factors achieved on space segments from the load factors achieved on rectennas, which are determined by different technical and market influences, permits the operation of each to be optimised. In particular it facilitates the achievement of higher load factors on the satellite than on the rectenna. These are desirable both because the satellite has a much higher capital cost than the rectenna, and because the value of daytime and peak electricity (that is, power with a lower load factor than base-load power) has greater value to utilities than base-load power.

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SPS 91

A2.6 Legal aspects of the use of SPS

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Abstract

In recent years, increasing attention has been focused on finding alternative sources of energy such as Solar Energy that is a constantly renewing one. Ambitious projects have been formulated using the Large Space Structure formulae to collect Solar Radiation. However, if one considers all the studies being published it can be stated that issues attending the development of such system are to be Political and Legal as well as technological.

As a Large-Scale Energy System, the Solar Power Satellite presents a plethora of answered and unanswered Legal questions. Among the Legal problems, some of the most crucial ones center around the Solar Energy collected, the basic Legal status of the Satellite itself and the regime of its operation. Any State or Company which proposes to undertake the Launching and the Assembly of a costly SPS network must clearly know in advance whether the project can be pursued as a National Endeavor or whether it will be subject to the constraints of some International Regime.

Résumé

Depuis quelques années, des recherches se sont orientées vers la quête de nouvelles sources d'énergie renouvelables et inépuisables telles que l'énergie solaire. Des projets ambitieux visant l'utilisation de centrales solaires en orbite terrestre ont été formulé. L'analyse de toutes les études publiées à ce jour démontre que le développement de ces structures dépend autant de questions politiques et juridiques que des réalisations technologiques.

Ces systèmes de captation d'énergie solaire soulèvent une multitude d'interrogations juridiques. Parmi celles-ci, le statut juridique de l'énergie solaire, des plateformes utilisées, ainsi que le régime de leur exploitation devront être précisés. Tout état ou toute entreprise ayant pour projet de lancer et assembler des segments aussi couteux, cherchera assurément à savoir à l'avance si ce type d'activité peut être poursuivi à l'echelle nationale et/ou s'il existe des régles internationales pouvant le régir.

A l'image de toute activité humaine, l'aventure spatiale entraîne les états ou les individus dans des relations particulières que le droit régle, dans le but d'éviter des conflits entre ces ces sujets de droit. Il pourra intervenir avant l'exploitation d'applications concrêtes ou a posteriori lorsque la phase opérationnelle soulève de nouvelles interrogations. Le juriste n'a pas pour objectif de prédire, il peut se satisfaire dés la conceptualisation d'une nouvelle forme d'activité, de simples projets.

Depuis le début de l'ére spatiale, les activités et le droit ont ainsi connu une évolution importante. La nature internationale et universelle de l'utilisation de cet environnement favorisa l'intervention de l'Organisation des Nations Unies, et plus spécifiquement de son Comité des Utilisations Pacifique de l'Espace Extra-atmosphérique (C.U.P.E.E.A.). Ce dernier, au travers de son sous comité juridique, joua depuis 1960 un rôle fondamental pour l'élaboration de conventions appropriées à ce domaine particulier. Sur la base de ses travaux, des principes formulés par diverses résolutions de l'Assemblée Générale des Nations Unies furent matérialisés dans une convention ayant force obligatoire, le traité sur les principes régissant les activités des états en matiére d'exploration et d'utilisation de l'espace extra-atmosphérique, y compris la Lune et les autres corps célestes, entré en vigueur le 10 Octobre 1967. Ce dernier constitue un cadre juridique général répondant aux besoins les plus éssentiels du développement de l'astronautique. A partir de cet instrument de base, et pour tenir compte des progrés de la navigation spatiale, les états membres du comité de l'espace ont adopté entre 1967 et 1979, quatre conventions venant préciser les droits et les devoirs des états partie au traité. Ce corps juridique est forme par l'accord sur le sauvetage des astronautes, le retour des astronautes et la restitution des objets lancés dans l'espace du 22 avril 1968, la convention sur la responsabilité internationale pour les dommages causés par des objets spatiaux du 22 mars 1972, la convention sur l'immatriculation des objets lancés dans l'espace du 14 janvier 1975 et l'accord sur la Lune du 18 décembre 1979 (cet accord est entré en vigueur le 11 juillet 1984 mais n'a été ratifié par aucune des puissances spatiales).

Ce droit élaboré dans le cadre des grands principes définis par ces conventions ne résume pas pour autant l'intervention de réglementations internationales spécifiques. Il faut aussi mentionner l'oeuvre des agences spécialisées des Nations Unies et surtout de Union Internationale des Télécommunications (U.I.T.) qui, depuis 30 ans, gére les fréquences radioélectriques et l'orbite géostationnaire. La poursuite de programmes spatiaux a elle même favorisé la création d'organisations internationales à vocation mondiale (INTELSAT, INMARSAT) ou régionales (ESA) et à la conclusion de multiples accord entre les puissances spatiales.

Avec la formulation de projets ambitieux faisant appel à des centrales solaires en orbite autour de la terre, captant le

rayonnement solaire et transmettant au moyen de micro-ondes cette énergie vers des stations terrestres, la discipline juridique se trouva confrontée à la conceptualisation d'une nouvelle activité. Le Comité de l'espace engagea, dès juin 1976, des discussions sur cette nouvelle technologie permettant une production massive d'électricité. Aucune disposition ne fut formalisée par les états membres mais il devenait évident que les centrales solaires ne seraient pas exploitées dans un vide juridique. Les principes de base du droit spatial pouvaient s'appliquer directement en attendant la promulgation de réglementations additionnelles se conformant a l'actualité technologique.

Cet exposé retracera donc l'état du droit existant définissant le statut juridique des segments utilisés et de l'environnement spatial (I), avant de préciser le régime juridique de l'utilisation des centrales solaires spatiales (II).

I- Statut juridique des segments utilisés et de l'environnement spatial

1- Sur terre

La portion terrestre du système est constituée par la centrale réceptrice et transformatrice des micro-ondes ou de tout autre faisceau transmis en electricité. Une surface relativement importante sera recouverte d'antennes recevant les transmissions des centrales en orbite. La complexité technique et le coût de tels sites pourrait permettre de promouvoir une internationalisation de leur statut, mais ceux-ci resteront à n'en pas douter sous la juridiction de l'état sur le territoire duquel ils seront exploités. Ils seront ainsi soumis au droit interne de cet état. Cependant, étant donné les possibles effets sur l'environnement de cette exploitation, des paramétres tels que la densité de la population locale, les données écologiques et la demande en electricité régionale, devront être pris en considération.

2- Les centrales solaires en orbite

Le statut juridique des centrales solaires en orbite demeure imprécis. Désignées par les termes "objets spatiaux" en droit conventionnel, elles ne sont pour l'instant sujettes à aucune réglementation spécifique. Toutefois, les états et les entités non gouvernementales autorisées et surveillées par ceux-ci, se proposant de développer de telles activités, sont soumis à des devoirs et bénéficient de droits particuliers. En premier lieu, des principes de rattachement juridique sont stipulés par l' article VIII du traité sur l'espace de 1967:

"L'état partie au traité sur le registre duquel est inscrit un objet lancé dans l'espace extra-atmosphérique conservera sous <u>sa juridiction et son contrôle</u> ledit objet et tout le personnel dudit objet...Les droits de <u>propriété</u> sur les objets lancés dans l'espace extra-atmosphérique...demeurent <u>entiers</u> lorsque ces objets...se trouvent dans l'espace".

Les états ne pourraient exercer des droits exclusifs que sur les centrales solaires spatiales qui sont inscrites sur leur registre nationaux. Cependant l'immatriculation constitue seulement une preuve <u>prima facie</u> pour attribuer la juridiction d'état, elle ne peut en être un facteur constitutif (il existe d'autres principes de rattachement juridique). Notons que la convention sur l'immatriculation de 1976 prévoit l'immatriculation nationale par les états de lancement, l'établissement d'un registre central tenu par le secrétaire général des Nations unies et des procédures supplémentaires pour une meilleure identification. D'autre part, l'intérêt général représente par le principe de libre navigation dans l'espace implique que les états n'exercent pas leur pouvoir législatif de telle manière à rendre ce principe inopérant.

3- L'environnement spatial

a)Le traité de l'espace de 1967, véritable "Magna Carta" des activités perpétrés dans l'environnement spatial, a formulé des principes dont certains revêtent une validité universelle d'application directe et effective. A ce titre, la liberté d'exploration et d'utilisation de l'espace est stipulée par l'article I(2) du traité:

"L'espace extra-atmosphérique, y compris la Lune et les corps célestes, peut être exploré et utilisé <u>librement</u> par tous les états sans aucune discrimination, dans des conditions d'égalité et conformément au droit international..."

Le refus du concept de souveraineté nationale, reconnu traditionnellement en droit international public, fait de l'espace extra-atmosphérique un milieu librement accéssible. Il s'agit bien d'un statut innovateur et cohérent qui permettra aux activités de captation d'énergie solaire de se dérouler sur une base juridique stable. Cette cohérence est renforcée par les limitations d'exercice de cette liberté:

(i) L'exploration et l'utilisation de l'espace doivent se faire pour <u>le bien et dans l'intérêt</u> de tous les pays, quel que soit le stade de leur développement économique et scientifique (Préambule et article I(1)). Bien qu'il ne soit pas ici question de partage de bénéfices ou d'avantages financiers, tout état partie au traité de 1967 devra s'assurer qu'un traitement équitable est appliqué à toutes les autres nations et ce quelque soit le stade de leur développement. Idéalement, la création d'un climat favorable à l'application de cette clause devrait passer par une évolution vers la détermination d'un intérêt international. INTELSAT est la parfaite illustration du type de coopération envisageable lorsqu'un tel intérêt est formulé et matérialisé par la communauté internationale.

(ii) Les activités des états parties au traité... doivent s'effectuer <u>conformément au droit international</u>, y compris la Charte de Nations Unies, en vue de maintenir la paix et la sécurité internationales et de favoriser la coopération et la compréhension internationales (article III).

(iii) Les états parties au traité s'engagent " à ne mettre sur orbite autour de la terre aucun objet porteur d'armes nucléaires ou de tout autre type d'armes de destrution massive...à ne pas placer de telles armes, de toute autre maniére, dans l'espace extra-atmosphérique..." (aticle IV(1)). L'exploitation de l'énergie solaire par le biais de plateformes spatiales doit se faire seulement à des fins pacifiques.

b) la liberté de l'espace est aussi assujettie à une régle prohibitive de droit positif formulée par l'article II du traité:

" L'espace extra-atmosphérique, y compris la Lune et les autres corps célestes, ne peut faire l'objet d'<u>appropriation</u> nationale par proclamation de souveraineté, ni par voie d'utilisation ou occupation, ni par aucun autre moyen.".

La rédaction de cet article, loin de régler certaines difficultés d'interprétation, laisse subsister des fragments de l'autorité étatique. Nous avons mentionné plus haut que l'exercice de la compétence matérielle et juridictionnelle sur les objets spatiaux est expréssement reconnue par l'article VIII. D'autre part, aucune portion de l'espace ou du soleil consideré comme un corps céleste, ne pourra faire l'objet d'une appropriation. Mais qu'en est-il des ressources naturelles non mentionnées dans cet article ? L'énergie solaire est elle considerée comme une ressource naturelle ?

4-L'énergie solaire

a) Il est tout d'abord primordial de présenter les qualités, pouvant avoir des implications juridiques, de l'énergie solaire. Les différents projets se proposent de tirer des benéfices de l'exploitation d'une ressource inépuisable,intangible, et renouvelable. Certains juristes n'ont pas hésité a la qualifier comme la plus importante de l'environnement spatial. Si le Soleil peut etre utilisé librement, la captation de son rayonnement bénéficiera de cette meme liberté et ne constituera pas une appro--priation au sens du droit spatial, étant donné son immaterialité et son renouvellement. L'utilisation de l'énergie solaire est même admise en droit coutumier inernational. Les satellites font réguliérement usage de panneaux solaires sans qu'aucun état ne s'y soit opposé. Une utilisation intensifiée pourrait toutefois remettre en question ce principe qui ne fut, par ailleurs, jamais officiellement reconnu.

b) Cette énergie est bien considerée comme une ressource naturelle malgré le manque de précision du droit conventionnel (cf.l'article 1 de l'accord sur la Lune). Rappelons que les états, créateurs du droit international public, ont voulu limiter leur liberté d'action dans un but précis: leur intérêt commun. Même si actuellement il semble impossible de mesurer l'étendue de cette limite, tout

équilibre qui pourrait être rompu entre l'article 1(1) du traité sur l'espace et cette même liberté porterait une atteinte grave à la construction du droit international de l'espace.

En reprenant ce principe, l'article 11 de l'accord sur la lune va plus loin lorsqu'il affirme que la Lune et ses ressources naturelles font partie du Patrimoine Commun de l'Humanité (l'article 1 étend l'application de l'accord au soleil et à ses ressources naturelles, incluant ainsi son rayonnement). Les états parties à l'accord s'engagent à établir un régime international régissant l'exploita- -tion des ressources naturelles de la Lune, lorsque cette exploitation sera sur le point de devenir possible (article 11(5)). Ce régime aura notamment pour but d'assurer la mise en valeur méthodique et sans danger de ces ressources naturelles, d'établir leur gestion rationnelle, de développer les possibilités d' utilisation et de ménager une répartiton équitable entre tous les états parties des avantages qui en résulteront; une attention spéciale étant accordée aux intérêts et aux besoins des pays en voie de développement ainsi qu'aux efforts des pays qui ont contribué soit directement soit indirectement à l'exploration de la Lune (article 11(7)). Or, même si cet accord entré en vigueur en 1984 n'a pas été ratifié par les puissances spatiales, il n'en constitue pas moins le reflet de l'inquiétude des états n'ayant pas encore participé à l'aventure spatiale. Le débat sur le partage des bénéfices invoqué par les pays en voie de développement connaîtra d'autres rebondissements dans les prochaines décénnies. L'exploi- -tation de l'énergie solaire sera à n'en pas douter, un chapitre important de ces discussions primordiales pour l'économie de nombreux états et pour lesquelles il faudra trouver des solutions répondant aux besoins de la communauté internationale.

II- Le régime juridique de l'utilisation des centrales solaires

Si la captation de l'énergie solaire ne constitue pas une appro- -priation, l'utilisation prolongée de fréquences et de positions orbitales par des centrales spatiales soulève certaines interrogations. Il en va de même pour les questions de reponsabilité dont les contours devront être précisés avant le début de la phase opérationnelle.

1-L'orbite géostationnaire et le spectre des fréquences radioélectrique

a) La zone orbitale occupée par les centrales solaires de façon quasi permanente peut faire craindre qu'on l'interpréte comme une appropriation de facto, non seulement à l'encontre du traité de l'espace mais plus pratiquement, cela peut priver une nation d'un site qui correspond exactement à ses besoins (pour ses satellites de télécommunications par exemple). étant donné la taille de ces installations et la limitation d'exploitation induite par les propriétés physiques de l'orbite géostationnaire, cette question revêt une importance primordiale.

Au cours d'une déclaration commune faite à Bogota, en décembre 1976, certains états équatoriaux (le Brésil, la Colombie, le Congo, l'équateur, l'Indonésie, l'Ouganda et le Zaire) considérérent l'orbite géostationnaire comme une ressource naturelle limitée et, revendiquérent l'arc se situant au dessus de leur territoire. Une crainte de l'affirmation d'un monopole était formulée, ce qui ne manqua pas de provoquer de vives réactions au sein de la communauté internationale. La majorité des états parties au traité sur l'espace rejetérent cet argument: l'orbite géostationnaire, faisant parte intégrante de l'espace extra- atmosphérique, ne peut faire l'objet d'aucune appropriation. Cette déclaration provoqua un changement d'attitude. Les fondements d'une utilisation rationnelle devait être constitués afin d'éviter toute interférence dans l'utilisation des segments spatiaux. Il en va de même pour le spectre des fréquences radioélectriques nécéssaire aux télécommunications avec les centrales solaires et à la transmission d'énergie par micro-ondes.

b) L'Union Internationale des Télécommunications se chargea d'aménager une utilisaton rationnelle de telles ressources en adoptant des dispositions en matiére d'emplacement sur orbite et d'allocation des fréquences. L'article 33 de la convention interna- -tionale des télécommunications (revue par la conférence des pléni- -potentiaires à Nice, le 30 juin 1989) mentionne effectivement que:

" 1. Les membres s'efforcent de limiter le nombre de fréquences et l'étendue du spectre utilisé au minimum indispensable pour assurer de manière satisfaisante le fonctionnement des services nécéssaires. A cette fin, ils s'efforcent d'appliquer dans les moindres détails les derniers perfectionnements de la technique.

2. ...les fréquences et l'orbite des satellites géostationnaires sont des ressources naturelles limitées qui doivent être utilisées de manière efficace et économique...afin de permettre un accés équitable à cette orbite et à ces fréquences aux divers pays".

Ainsi, les conférences administratives mondiales de radiocommunications (surtout la CAMR-ORB de 1985 et la CAMR-ORB de 1988) se sont attachées à concilier le principe d'accés garanti et équitable avec l'utilisation économique et efficace de ces ressources. Malgré ces efforts, la mise à poste de grandes plateformes sur l'orbite géostationnaire demeure encore un sujet de reflexion pour le juriste. M. Gabriel Lafféranderie se demandait à juste titre, lors de sa présentation sur ce même sujet en 1986, si les états parties au traité sur l'espace laisseraient se développer en dehors d'eux un systéme spatial qui occuperait une place significative sur cette orbite déjà si recherchée. Il faudra pour le moins éviter tout conflit entre les nations afin de permettre la subsistance d'une planification internationale si délicate.

En ce qui concerne le spectre des fréquences radioélectriques, la conférence administrative mondiale des radiocommunications de 1979 décida que les centrales solaires spatiales ne constitueraient pas un nouveau service. L'utilisation des fréquences pour les les communications avec ces centrales seront régies par les dispositions s'appliquant aux services spatiaux déjà établis.

En matiére de transmission de micro-ondes des centrales en orbite vers les antennes au sol, la compétence de l'UIT fut recommandee lors de cette même conférence. Son rôle de répartiteur et de coordinateur de fréquences permettrait d'éviter toute interférence avec des services existants (cf. par exemple, l'article 35(1) de la convention internationale des télécommunications et article 1 des réglements des radiocommunications). L'action entreprise par l'UIT devra néanmoins intervenir avant le développement de ces centrales étant donné les répercussions potentielles pouvant toucher un grand nombre d'utilisateurs des fréquences radioélectriques (pour les communications terrestres ou aéronautiques, les télécommunications spatiales, les systémes de détection et de radars,etc.).

2- La responsabilité des dommages causés par les centrales solaires spatiales

De par la taille des structures en cause, il existe des risques de collisions avec d'autres objets spatiaux et d'accidents lors des lancements d'éléments devant être assemblés dans l'espace. Le droit spatial a défini avec précision les régles de responsabilité s'appliquant aux dommages survenus au cours de tels événements. On ne peut, par contre, répertorier toutes les consequences possibles des transmissions d'énergie sur l'homme et l'environnement. Il sera donc parfois difficile de relier la cause à l'effet et d'evaluer l'ampleur du dommage.

a) Dans le contexte des utilisations de l'espace, la grande majorité des juristes ainsi que des délégations nationales au Comité des Utilisations Pacifiques de l'espace extra-atmosphérique s'orienterent trés tôt vers l'adoption d'un systéme de responsabilité exclusivement imputable aux états. Une telle attitude fut corroborée par l'article VI du traité sur l'espace. Les états parties au traité ont la responsabilité internationale des activités nationales dans l'espace, qu'elles soient entreprises par des organismes gouvernementaux ou par des entités non gouvernementales, et veillent à ce que les activités nationales soient poursuivies conformément aux dispositions du traité. Les activités des entités non gouvernementales font l'objet d'une autorisation et d'une surveillance continue de la part de l'état approprié. Dans l'éventualité d'une captation de l'énergie solaire effectuée par une entreprise privée, un régime d'octroi de licence et de surveillance devra être adopté par le droit interne de l'état exerçant une compétence personnelle. D'autre part, l'article 7 du traité sur l'espace vient préciser que:

" Tout état partie au traité qui procede ou fait procéder au lancement d'un objet dans l'espace...et tout état partie dont le territoire ou les installations servent au lancement d'un objet est responsable du point de vue international des dommages causés par ledit objet ou par ses éléments constitutifs, sur la terre, dans l'atmosphére ou dans l'espace extra-atmosphérique, y compris la Lune

et les autres corps célestes, à un autre état partie au traité ou aux personnes physiques ou morales qui relèvent de cet autre état". La convention du 22 mars 1972 sur la responsabilité internationale pour des dommages causés par des objets spatiaux est venu clarifier et développer la teneur de cette disposition. Une responsabilité absolue indépendante de toute faute, est consacrée dans l'article II traitant des dommages causés par un objet spatial à la surface de la terre et aux aéronefs en vol. L'article prévoit une responsabilité délictuelle éxigeant la preuve que l'acte préjudiciable ait été dû à la faute ou à la négligence de l'état ou des personnes dont cet état répond. Ceci ne concerne que les dommages causés ailleurs qu'à la surface de la terre à un objet spatial ainsi qu'à des personnes ou à des biens se trouvant à bord de ce dernier. Dans tous les cas le dommage désignera la perte de vies humaines, les lésions corporelles ou atteintes à la santé, ou la perte de biens d'état ou de personnes physiques ou morales, ou de biens d'organisations internationales intergouvernementales (article 1(a) de la convention). La définition donnée est donc particulièrement large, permettant d'y inclure les conséquences des développements de centrales solaires en orbite et constituer un gage de sécurité pour les victimes potentielles.

b) Au delà de la collision ou du lancement d'objets spatiaux traités par la convention, les perturbations liées à la transmission d'énergie restent soumises à un statut incertain. Or, même si certains préjudices comme le préjudice écologique ne sont pas mentionnés, les dommages matériels semblent definis de façon complète, couvrant ainsi les conséquences de ce type de transmission. Ainsi, les états utilisant des techniques de transmission d'énergie qui pourraient avoir des effets néfastes tels que la perte de vie humaine, les lésions corporelles ou atteintes à la santé et les dommages à la propriéte, seront tenus responsables. L'abscence de normes internationales en matiére d'exposition humaine à ce genre de faisceaux de transmission n'est pas déterminant quant à l'établissement de la responsabilité.
Notons que les interférence nuisibles aux autres utilisateurs de l'espace et les dommages à l'environnement ne résultant pas par des atteintes à la santé ou à la propriété, ne sont pas couverts par la convention. Seul l'article IX du traité sur l'espace s'appliquera an disposant que:
" Les états parties au traité devront se fonder sur les principes de la coopération et de l'assistance mutuelle et poursuivront toutes leurs activités dans l'espace...en tenant <u>dûment compte des intérêts correspondants de tous les autres états parties au traité</u>...(ils) procéderont à leur exploration de manière à éviter ...les modifications nocives du milieu terrestre résultant de l'introduction de substances exta-terrestre".
Des consultations entre états devront s'établir dans le cas où un état aurait lieu de croire qu'une activité envisagée par lui même ou par un autre état dans l'espace causerait une gêne potentielle--ment nuisible aux activités des autres états parties au traité sur l'espace (se référer aussi à l'article IX). Le manque de précision de cet article en réduit néanmoins sa portée. Les conséquences de l'utilisation des centrales solaires sur l'environnement spatial et terrestre devront pourtant être contrôlées et réglementées en faisant appel au droit international. Il faudra toutefois pour cela une correlation entre le choix d'un projet et la production d'étude techniques, permettant d'aider le juriste dans sa tâche.

Conclusion

Le droit spatial dispose de principes de base s'appliquant directement aux centrales solaires qui seront exploitées dans l'espace. L'application de la liberté d'utilisation, de la clause d'intérêt commun, de la prohibition de toute appropriation ou de la responsabilité des états pour leurs activités spatiales n'est plus à remettre en cause. L'actualité technologique tend cependant à transformer rapidement les scénarios d'exploitations envisagés pour ces centrales. Un cadre juridique flexible et stable, se conformant à ces évolutions et contribuant à une utilisation optimale, devra être ainsi determiné sur la base des principes fondamentaux et de dispositions spécifiques. Ces dernières porteront notamment sur la définition du statut juridique des ségments utilisés et de l'énergie solaire, de l'utilisation des ressources naturelles limitées, de la coopération internationale et de l'impact de telles activités sur l'environnement terrestre et spatial. Dans ce contexte, la tendance materialisée par la déclaration de Bogota ne pourra etre ignorée. Les états membres du comité de l'espace des Nations Unies ont d'ailleurs récemment introduit un nouveau sujet de négociation sur les aspects juridiques du principe selon lequel l'exploration et l'utilisation de l'espace doivent se faire dans l'intérêt de tous les états, en tenant particuliérement compte des pays en développement. L'exploitation spatiale de l'énergie solaire fera assurément partie de cette réflexion.

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A3.1 Nonterrestrial resources for solar power satellite construction

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RESUME

Cet article fait la revue des concepts d'edification de satellites affectes à la production de puissance helio-électrique à partir de matériaux d'origines etra-terrestres. Le besoin de nouvelles methodes simples de transformation de matériaux et de développment de systèmes de production est souligne. La démonstration du concept de transmission de puissance à partir de satellites pour une utilisation de l'energie sur la surface lunaire est suggere dans cette communication.

SUMMARY

This paper reviews the concept of building solar power satellites from lunar and other nonterrestrial materials. The need for simple material processing techniques and the development of manufacturing systems is emphasized. The use of power beaming demonstration satellites for lunar power is suggested.

The construction of economically viable solar power satellites will require the transport of large quantities of building materials as well as consumables and propellants. Most of the studies on Solar Power Satellite construction undertaken to date, have assumed that these materials would originate on the surface of the Earth, be launched aboard heavy lift rockets to low Earth orbit and then ferried to construction sites in geostationary orbit.

The high costs of space transportation provide a fundamental impediment to any large space effort. Although a project the size of SPS would benefit from economics of scale effects, the absolute size and cost of the equipment required for terrestrial launch poses a considerable challenge. Figure 1. shows a comparison between the present Space Shuttle and a 500 tonne to LEO reusable heavy lift launch vehicle proposed for SPS transport use. Uncertainties regarding the high cost of space transportation were an important reason that SPS research was not continued beyond the NASA/Department of Energy studies of the late 1970's.

In addition to the issue of direct monetary costs, the large number of launches required for implementation of a space power system require close attention to environmental impact. Primary areas of concern in this area relate to the deposit of reaction mass materials in the upper atmosphere and sonic effects of launch and overflight.

The twin problems of high Earth-to-orbit launch costs and the possible need to minimize deleterious environmental effects produced by the very large mission model required for SPS scale construction can be addressed by considering alternatives to the Earth as a source of raw materials. In 1969 (approximately the same time in which Dr. Peter E. Glaser was pioneering the Solar Power Satellite concept) Dr. Gerard K. O'Neill was exploring the concept of constructing large systems in space from materials obtained from nonterrestrial sources.

O'Neill observed that the amount of energy required to launch materials from the Earth's moon to escape velocity was less than one twentieth of that required for Earth escape. Figure 2. depicts the relative energies required for Earth escape as "gravity wells." The amount of energy required for Earth escape for example, is about the same as lifting the launch mass 4,000 miles. The moon, by comparison, is situated in a sort of "gravity dimple." Asteroids are scattered about the surface of the plateau of free space in this analogy.

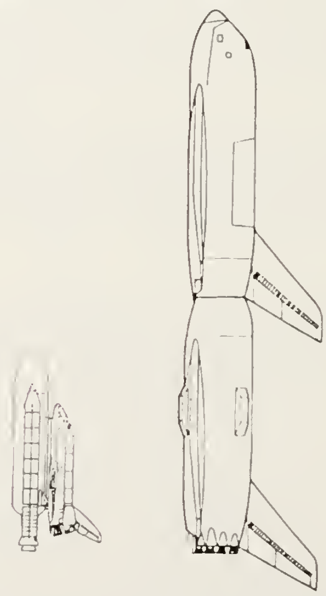
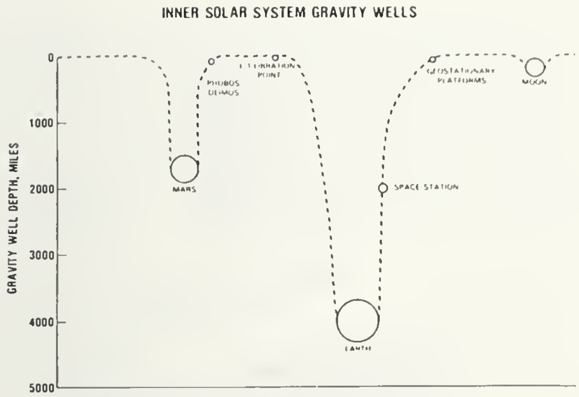


Figure 1. Comparison between Space Shuttle and SPS Heavy Lift Launcher



Source: President's National Commission on Space

Figure 2. Gravity Well depiction of relative energy required for escape

O'Neill proposed the construction of habitats in free space constructed from lunar materials in 1974. [1] He proposed taking advantage of the low gravity and lack of lunar atmosphere by using an electromagnetic launcher to throw a stream of pellets of lunar soil to a collection point in space with high efficiency. The material would be processed in free space using solar energy. In 1975 O'Neill applied the idea of using lunar resources to the task of constructing solar power satellites. Material launched into space with the electromagnetic launcher (called a mass-driver) would be processed at a space manufacturing facility, possibly located at one of the Lagrange points in the Earth-Moon system.[2]

The space manufacturing facility would consist of processing plants, fabrication shops and construction facilities as well as provisions for the long term habitation of the construction personnel, support staff and their families. The habitats would provide artificial gravity produced by rotation, radiation shielding provided by liberal use of slag and other waste products of lunar processing. A high degree of closure in the life support system would also be provided with most of the food required by the inhabitants grown locally.

O'Neill also Introduced the concept of "bootstrapping" in 1975. Bootstrapping refers to using the initial lunar and space construction facilities to produce partial replicas of themselves in order to achieve exponential growth of production capability.

Although the U.S. government studies of space solar power were generally predicated upon the launching of all construction and support materials from the Earth, two studies on the use of nonterrestrial materials for SPS were supported during the NASA/DOE investigations. These projects were undertaken by the Massachusetts Institute of Technology (MIT) [3] and the Convair Division of General Dynamics. [4] These studies examined the NASA/DOE selected baseline design for an SPS in geosynchronous orbit and looked at constructing this design from lunar materials. The studies concluded that between 90% and 96% of the mass of a solar power satellite could be lunar in origin.

The General Dynamics study looked at four different ways to produce a solar power satellite. It examined the baseline case of launching solar power satellite construction materials to low Earth orbit, ferrying them to Geostationary orbit for construction. The next concept (called Lunar Resource Utilization [LRU] Concept B) was the O'Neill scenario of launching raw lunar soil using electromagnetic launch, with processing and fabrication taking place at a Space Manufacturing Facility. The study also looked at performing the processing on

Facility. The study also looked at performing the processing on
the lunar surface and launching building materials using lunar oxygen with Earth-imported hydrogen (LRU Concept C) and lunar oxygen with lunar aluminum (LRU Concept D) Figure 3. shows a graphic depiction of these four scenarios. Figure 4. shows the components of the classical electromagnetic launch scenario.

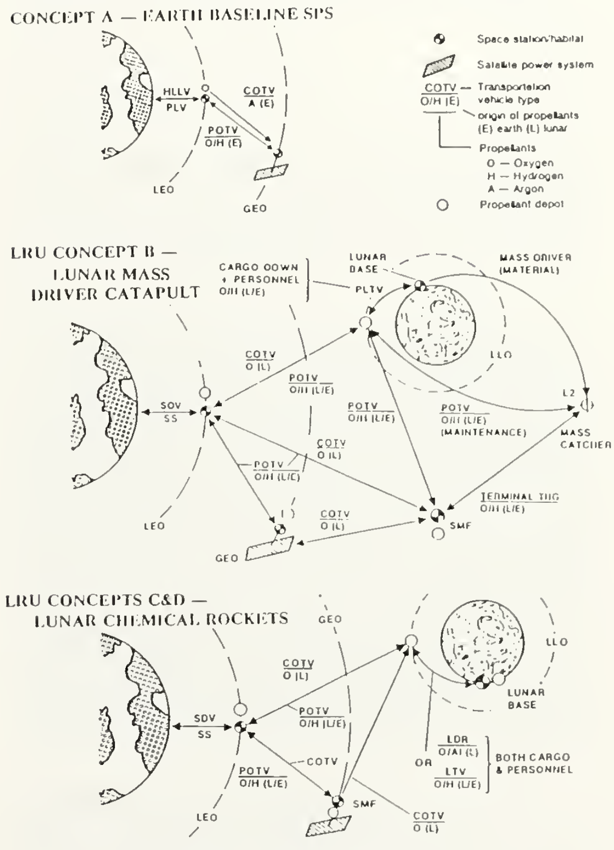


Figure 3. General Dynamics SPS Scenarios

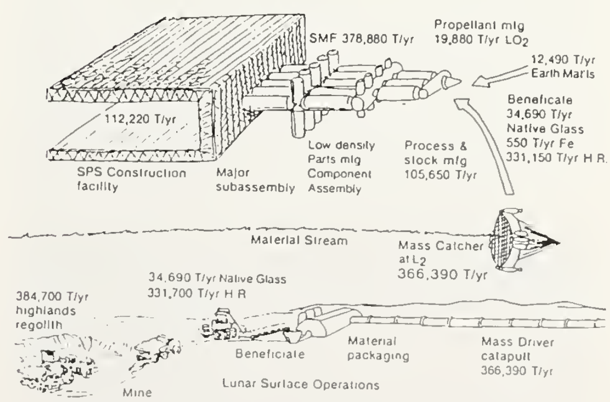


Figure 4. Components of Lunar Electromagnetic Launch Scenario (LRU Concept B.)

All three lunar resource utilization scenarios resulted in dramatically lowered Earth launch requirements. (See Figure 5.) Electromagnetic launch resulted in the lowest Earth launch needs and the lowest cost per power generation capacity as depicted in Table 1.

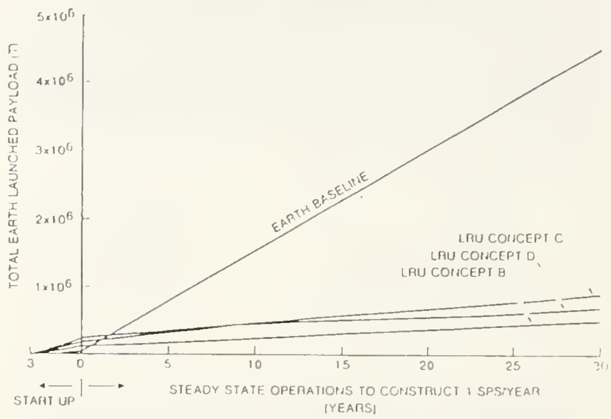


Figure 5. Relative Earth launch requirements for SPS (General Dynamics)

Neither the MIT study nor the General Dynamics study intended to redesign the SPS in order to take maximum advantage of the use of lunar materials. Instead, the baseline design was modified within limits. In order to go beyond the NASA/DOE sponsored work, a study was commissioned by the Space Studies Institute of Princeton, New Jersey. The purpose of this study was to reexamine the range of SPS configurations and optimize the design to achieve the highest possible percentage of nonterrestrial (lunar) SPS mass. Space Research Associates of Seattle, Washington was selected as the study contractor in a process initiated with an SSI request for proposals. The RFP was drafted by a team which included Dr. Gerard K. O'Neill of SSI and Princeton University, Dr. Peter E. Glaser, Mr. Edward Bock, principal investigator for General Dynamics' SPS study, Dr. John Freeman of Rice University, Mr. Gordon Woodcock of Boeing Aerospace, Dr. Les Snively of SSI and this author.

	Earth Baseline	LRU Concept B	LRU Concept C	LRU Concept D
RDT&E & startup ($/kW)	235.3	405.9	451.6	485.9
SPS hardware	21.0	21.0	21.0	21.0
Construction system	69.0	69.0	69.0	69.0
Facilities & equipment	55.7	229.3	253.0	277.7
Transportation	89.6	86.6	108.6	118.2
Production ($/kW)	2188.3	994.4	1127.2	1048.9
Earth-based fab & assy	2066.7	764.9	848.1	794.7
Lunar-based fab & assy	0	9.8	61.4	84.9
Space-based fab & assy	121.6	219.7	217.7	169.3
Operations ($/kW)	622.2	622.2	622.2	622.2
Total program cost ($/kW)	3045.8	2022.5	2201.0	2157.0

Table 1. Relative system costs (General Dynamics)

The study examined six basic designs. These included two which were found most promising, a silicon planar design which resembled the NASA/DOE baseline, and a gallium arsenide cell design using solar concentrators. Four other conversion systems were investigated: thermophotovoltaic conversion, Brayton cycle turbogenerators, Rankine cycle turbogenerators and Stirling cycle engines. These were found to use significantly more non-lunar material than either the silicon or gallium arsenide systems. Figure 6 shows a comparison between these systems (including two different Brayton cycle temperatures) in terms of non lunar kilograms per kilowatt. Figure 7 shows the total specific mass comparison of the same systems.5

It was found that a silicon planar SPS can be designed which requires less than 1% of its mass as Earth-launched material. The total mass of the system is about 8% greater than a completely Earth-sourced design. Figure 8 shows a mass comparison between the Boeing (Earth baseline), General Dynamics and SSI/SRA study designs.6

The Solar Power Satellite studies of the 1970's examined many of the construction issues as well as the environmental and economic factors involved in implementing space power systems. This work remains valuable, despite improvements in technology in such areas as photovoltaics. The construction of solar power satellites from lunar materials would not necessarily be a radically different enterprise from a construction point of view. What obviously does change is the need for development of a space infrastructure to provide construction components to the SPS worksite.

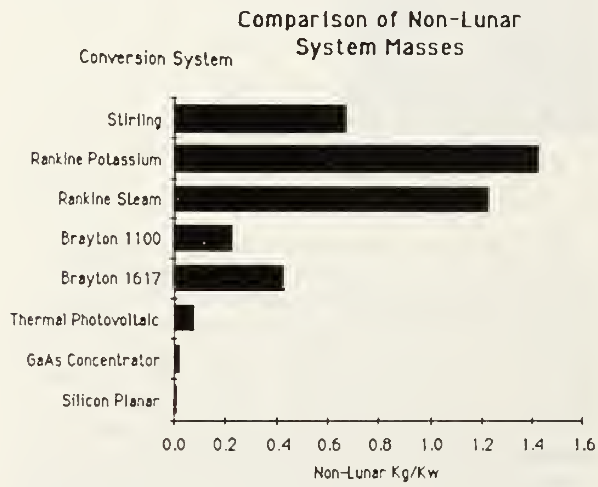


Figure 6. Non-lunar mass comparison of solar power conversion systems

This infrastructure breaks down into several key categories. These include location of candidate materials, excavation and mining operations, transport from the lunar surface into space, processing of lunar materials into construction feedstocks and fabrication of solar power satellite system components from these feedstocks.

In order to accelerate the development of space resources, O'Neill founded the Space Studies Institute in 1977.7 SSI has undertaken a course of research aimed at testing and demonstrating critical technologies required to provide space solar power to the Earth. The balance of this paper reviews, research conducted to date by SSI with respect to the development of the space resource infrastructure described above and looks at areas which require further attention.

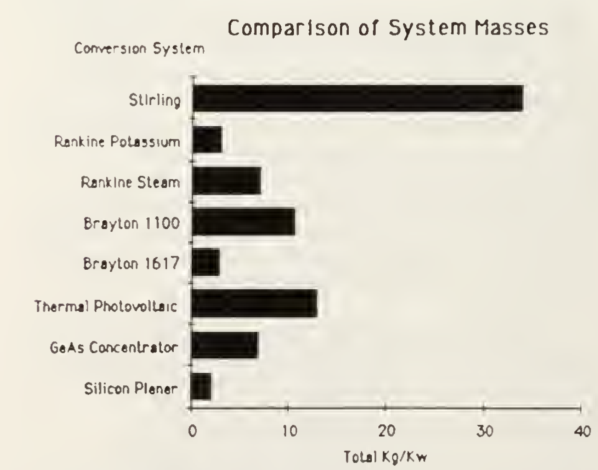


Figure 7. Total specific mass comparison of solar power conversion systems

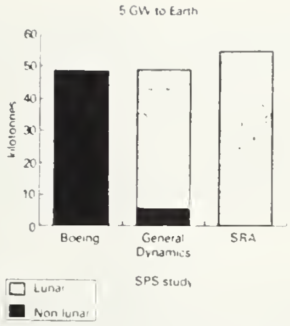


Figure 8 Mass comparison between Earth baseline, Early lunar and lunar optimized SPS designs

SSI's first technology development project was the Mass Driver electromagnetic launch system. O'Neill and Kolm constructed a proof of concept mass-driver at MIT during the 1976-1977 academic year. This machine was demonstrated at the Princeton Conference on Space Manufacturing in May of 1977. Using silicon controlled rectifiers to gate power from capacitors, this first test device demonstrated an acceleration of 33 gravities. A second device was developed and tested at Princeton University with support from NASA and SSI. This machine, dubbed Mass Driver II, demonstrated accelerations of 500 gravities. It also demonstrated magnetic flight for the bucket, the container that would hold the lunar soil payload while it traverses the length of the machine. Complex control circuitry and power handling and management were also incorporated in this design.

In order to test a less complex geometry mass driver, with bucket centering forces obtained from the drive coils rather than a magnetic flight system, a third mass driver was constructed at Princeton by SSI. This machine demonstrated accelerations of over 1,800 gravities. With this level of acceleration, a lunar mass driver would require an acceleration section of 160 meters in length in order to achieve lunar escape velocity of 2.4 kilometers per second.

Additional work required in mass driver development includes developing a means of providing power to the moving bucket during its traverse of the system. Developing a precise system of velocity control for the bucket and payload to permit precise targeting of the payload stream to a catching facility at Earth-Moon L2 with a minimum of downrange correction beyond the mass driver is also necessary.

Overall high fidelity computer modeling of the flight of payloads from the lunar mass-driver to the mass-catcher at Earth-Moon L2 is also a goal for future research. This work will build on work already accomplished on the accuracies possible with mass-driver systems.8

Advanced power switching and power conditioning technology has been developed in connection with SDI applications of electromagnetic launch technology. Although the accelerations required for these military technologies is much higher than that required for lunar launch, application of these tools appears useful to the lunar case. Preliminary investigations are also underway regarding the possible benefits of using high temperature superconductors for electromagnetic launch.

Several alternative scenarios are also being explored for the serial launch of payload from the surface to the Moon into space. Snow and Andrews proposed the use of "smart buckets" for the delivery of lunar oxygen to lunar orbit.9 Woodcock, Buddington et. al. have recently furthered this concept.10

Laser energized rockets have also been proposed as a means of delivering lunar materials to the plateau of free space.11 The lack of atmosphere which tends to distort the laser beam makes this approach appear much less challenging than for a terrestrial laser launching system. Further, though such a system would be less energy efficient than an electromagnetic launcher, it could also be used to land payloads on the lunar surface.

Processing of Lunar Materials

While a great deal of research over the past two decades has examined the issue of transportation within cis-lunar space, only recently have resources been brought to bear on one of the most pivotal requirements for SPS construction from lunar materials. This area is that of the processing of raw lunar materials into construction feedstocks.

Early thought in this area was that since the Moon contains materials similar to those used in terrestrial aerospace industry products (aluminum, titanium etc.) that these materials would be used for space construction. Initially it was also assumed that a relatively wide range of elements would be extracted from raw lunar soil. Relatively complex chemical processes such as the carbothermal process were initially considered. Under contract to SSI, Rockwell International performed bench chemistry experiments to discern reaction rates and other parameters of a "whole soil" HF acid leaching technique which produced a broad range of output products.12

Eventually, such a broad range of products will be useful and essential to the growth of industrial capacity in space. However, it appears to be more cost effective during the early stages of the development of a space infrastructure to concentrate on simple, robust systems which produce a single product or a modest range of products.

One product which appears quite interesting for SPS construction is a fiberglass-like composite made from lunar glass. Terrestrial fiberglass is made up of glass fibers imbedded within a plastic (usually hydrocarbon based) matrix. Goldsworthy Engineering of Torrance California demonstrated an engineering prototype of a machine which could manufacture composite truss structures for Solar Power Satellites during the late 1970's. Grumman Aerospace also experimented with composite materials following their experience with aluminum truss structures and an aluminum beam builder demonstration. 13

For several years, SSI, under the direction of W. Brandt Goldsworthy has conducted an experimental program to develop a glass / glass composite from lunar materials using simulants. This material would have a lunar glass matrix with a lower melting temperature than its lunar glass fiber components. Small samples of the glass / glass composite material have been produced in the laboratory. Future work will attempt to develop means of lowering the melting temperature of the matrix by the appropriate selection of fluxes, hopefully lunar in origin. The existing materials have a melting temperature similar to present day thermoplastics.14

In addition, a project is currently under way to develop a pilot scale production facility for lunar glass composites and other simple thermally processed materials from lunar simulant using solar thermal energy. This joint project is being carried out under the auspices of Alcoa/Goldsworthy Engineering, McDonnell-Douglas Corporation and the Space Studies Institute. Using an 11 meter solar concentrator at the McDonnell Douglas Huntington Beach Facility, this project has produced simple glass fibers as well as cast basalt rods and bricks. Figures 9. and 10. depict the present test facility.

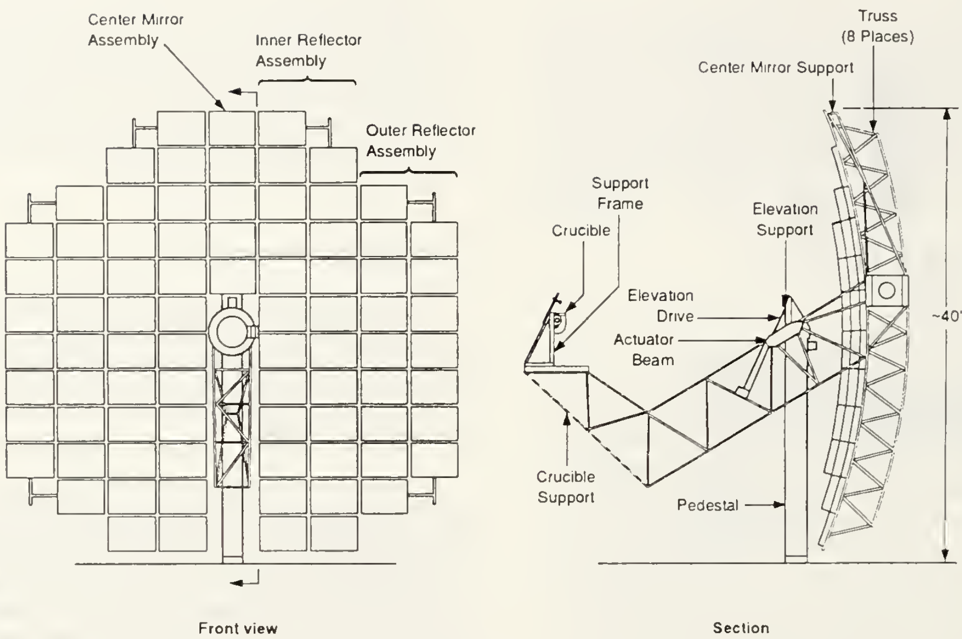


Figure 9. Solar powered lunar pilot processing rig schematic (McDonnell Douglas)

Another type of physical processing that may yield building materials for space construction is the magnetic separation of iron deposited In lunar regolith by meteoric bombardment. Agosto proposed separating these materials and using the resultant fine grains of iron to make parts vla powder metallurgy techniques.15 Oder has demonstrated magnetic separation using actual lunar soil samples returned by Apollo.16

At the next level of processing complexity are electrochemical processing techniques. Haskln has proposed melting lunar soil and electrolytically obtaining oxygen and other elements. He has performed experiments with gram-sized amounts of lunar simulants using platinum wire as the electrodes.17 Keller has proposed melting lunar anorthite in a molten salt and electrolytically obtaining silicon for solar cell production, as well as oxygen, aluminum and calcium. 18 Keller and Haskin are jolntly examining questions of electrode life and other operational concerns regarding electrolytic processing.

Waldron has proposed recovering oxygen and iron from lunar soil by a process that would initially melt iron rich (mare) soil in the presence of oxygen, dissolve magnetic spinel phases in electrochemically stable aqueous mineral acids and electrolyze the resultant solutions to obtain the products. 19

Construction materials may also be obtained as byproducts from processes primarily intended for the production of propellants. For example, hydrogen reduction of lunar ilmenite to obtain oxygen has received a relatively large amount of study. Briggs and Sacco have examined means of obtaining iron as a byproduct of this process.20

The adaptation of familiar processes to the microgravity environment is a relatively unexamined challenge to the chemical engineering community. It remains to be seen whether the space environment will provide a more difficult or less difficult area of operations for processing than is a planetary body.

While systems for processing lunar materials are in the early stages of development, there is one important area regarding the use of nonterrestrial materials that has received only first approximation analysis. That area is the in space fabrication of component parts for space systems. Workshops by NASA 21 and SSI22 have begun an examination of the application of highly automated production technologies to space construction. Extrapolations have been made using automated automobile production as a basis for prediction.

Because of the cost benefit of using lunar (or other

Figure 10. Solar powered lunar pilot processing rig in operation (McDonnell Douglas)

nonterrestrial) materials over Earth-launched materials,23 interest has been shown in the concept of constructing a system of space hardware that can replicate most of its own mass. O'Neill described a 200 tonne system on the moon and in free space that could manufacture 95% of its own components from lunar materials during a 90 day "doubling period.24 The potential of this concept is illustrated in cartoon form in Figure 11. In three 90-day generations, such a system would have 7 "descendants" with a combined processing capability of 12,600 tonnes per year.

Noting the benefits to space manufacturing, the National Research Council of the U.S. National Academy of Sciences has shown interest in self-replication systems. It suggests that development of such systems be funded as one of six grand challenges in computer science and technology. 25

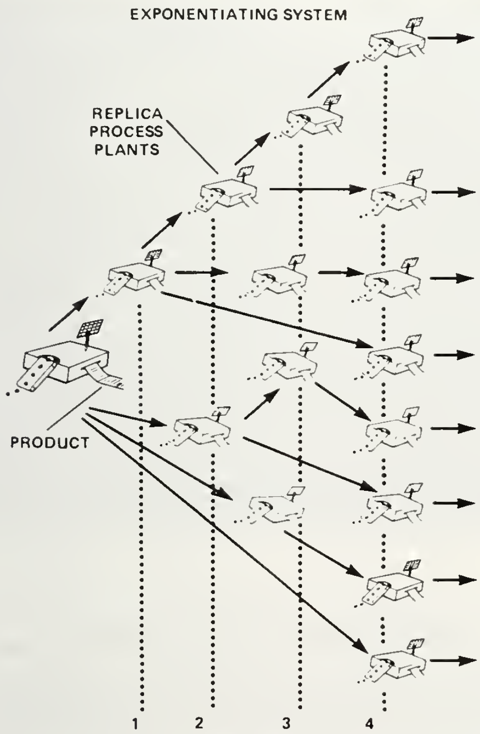


Figure 11. Self-replicating system growth (NASA CP-2255)

Some attention is now beginning to be devoted to the production of solar cells from lunar materials. 26 However, this is an area that requires further work. In the absence of data it is difficult to predict the level of difficulty required for this task. One suggestion that has been proposed by Space Research Associates in its SSI study and by Woodcock in the NASA Lunar Energy Enterprise case study would be to use terrestrially sourced photovoltaics operated at high concentration ratios. The bulk of the SPS mass including structure and solar concentrators would be derived from lunar materials. Figure 12. depicts an SRA design for a concentrator system that uses the optics as part of the heat rejection system that cools the solar cells. Figure 13. shows an alternative system proposed by Woodcock 27 using Fresnell lens concentrators made of lunar glass.

Recognizing that the most economical space power systems might at first not be those with the highest percentage of nonterrestrial materials, SSI commissioned a second SPS study by SRA. This project has begun to examine designs for solar power satellites that use only simple, minimally processed lunar materials.28

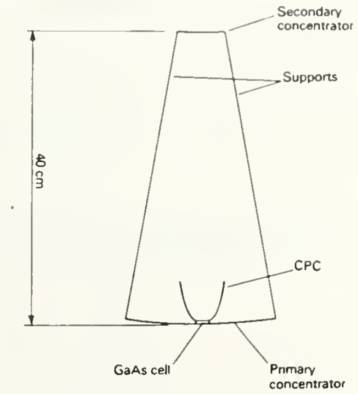


Figure 12. Solar concentrator for Gallium Arsenide system (SRA)

As the development of tools and techniques for space processing and construction proceeds it will be essential to conduct trade studies to determine the optimum balance between use of prefabricated subsystems and materials launched from the Earth and creation of space infrastructure to manufacture components from raw materials in space. This balance will tend to shift towards complete use of nonterrestrial materials as the space infrastructure matures and becomes more complex. In doing so space systems will repeat the history of earth exploration and settlement.

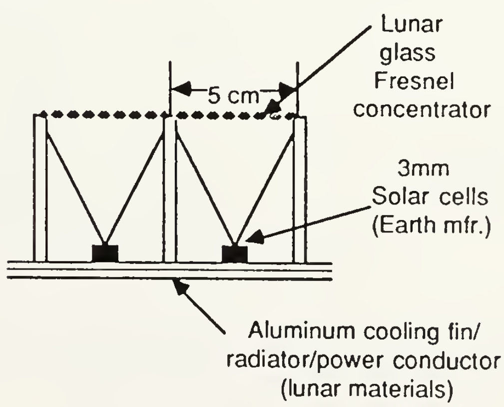


Figure 13. Fresnell-type solar concentrator (NASA TM-101652)

All of the studies of SPS construction have assumed human presence. Regardless of the degree of automation and teleoperation that proves practical it appears that on-site personnel will be required. Nonterrestrial materials can provide the bulk shielding from radiation that will be required for long stays beyond low Earth orbit. These materials can also provide for structures of sufficient size to provide artificial gravity against bone loss and other negative biological effects of the microgravity environment. Experimentation to determine the level of pseudogravity required is essential.

While the Moon appears to be the most promising source of nonterrestrial materials for SPS construction, other options include near-Earth and other asteroids. Table 2. shows some of the features of space resources in general. Since, on average the asteroids are about 1000 times more distant than the moon, significant life support or very advanced automation will be required for asteroidal utilization. However, our knowledge of small bodies in the solar system is extremely limited. Search programs such as those conducted by Helin using traditional methods and the new CCD imagers operated by Gehrels are of enormous value and should be accelerated.

Sources of Nonterrestrial Resources:

Location	Type	Positive Factors	Negative Factors
LEO	External Tanks	Low Delta V.	Will impact Earth if not controlled.
		Known Material.	
		Near Initial Markets.	Limited Resource (but Shuttle-C and Buran flights will add material.)
		Easy teleoperarions	
Cislunar	Lunar Materials	Low Delta V.	Requires propulsive landings.
		No atmosphere to impede serial launches.	2 weeks of darkness.
		Known Composition (at landing sites.)	
		Oxygen , Iron, Glass, Silicon, Helium-3, Sheilding mass.	
		Frequent mission opportunities for logistics and rescue.	
	polar volatiles	propellants, life support and chemical reagents	*existence unknown at this time*
Translunar	Asteroids (and very small moons)	Low Delta V	Long synodic periods (infrequent mission opportunities.)
		no high impulse maneuvers needed.	
		Iron, Nickel,Hydrogen, Carbon, Nitrogen,Oxygen, Water Ice.	Long travel times.
			Long signal times. (no teleoperations.)
			poor data on lacations and composition at present
Planetary Surfaces and Atmospheres	Mars	Base uses such as structures, life support and local use propellant.	Deep Gravity Wells. No teleoperations. No likely exports.. Long travel times

Table 2. Nonterrestrial Materials Characteristics

Finally, it should be recognized that although the data returned by the Apollo and Luna missions to the moon enables serious consideration of the use of lunar materials, our knowledge of the mineral content of the Moon is quite incomplete. Figure 14. shows the areas of the moon which have been chemically mapped using gamma-ray spectroscopy from lunar orbit. The moon's polar regions have not been mapped although they may contain frozen volatiles of great benefit to space transportation and chemical processing.

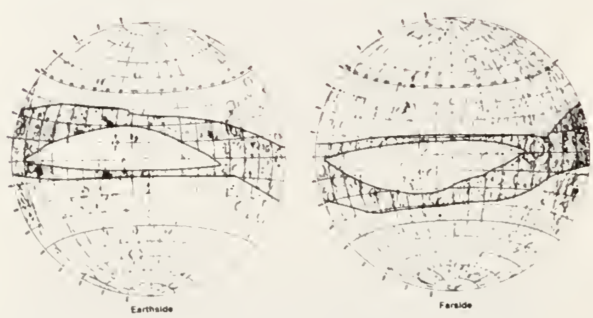


Figure 14. Areas mapped via gamma-ray spectroscopy during Apollo

In order to return chemical mapping data as soon as possible, a modest spacecraft called Lunar Prospector has been proposed by SSI. NASA has agreed to provide a surplus Apollo gamma-ray spectrometer to the project. A Lunar Prospector Consortium has been formed to complete the design and construction of the spacecraft which has been designed to fly as a secondary payload. The craft, which weighs approximately 300 kilograms fueled, is autonomous of its launcher after release in geostationary transfer orbit around the Earth. Figure 15. shows the full scale mockup of the spacecraft.

The use of space resources for the construction of solar power satellites will require electrical power on the lunar surface and in cis-lunar space far beyond space station demands.

Figure 15. Full-scale mockup of *Lunar Prospector* spacecraft (SSI)

We are presently investigating the feasibility of transmitting power from the Earth-moon L1 point to the lunar surface. Many investigators have discussed low Earth orbit platforms to demonstrate beamed power operations and to further examine space to Earth power propagation characteristics. Our investigation will look at the possibility of designing such a platform to later serve as part of a lunar base power system.

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A3.2 Economic impact of using lunar resources to build SPS systems

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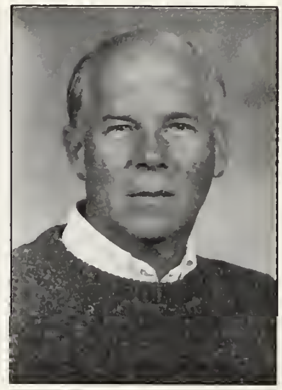


RESUME

L'argument le plus souvent cité par ceux qui s'opposent aux centrales SPS est le coût élevé de l'électricité délivrée au niveau du jeu de barres. Une comparaison correcte des prix devrait tenir compte des économies liées à la non pollution de l'environnement. L'emploi des ressources lunaires pour la construction des centrales SPS permettrait de réduire les coûts de lancement et d'éviter la pollution par les gaz d'échappement des fusées. Ce double avantage devrait permettre de rendre les centrales SPS plus attractives au plan économique.

ABSTRACT

L'argument le plus souvent cité par ceux qui s'opposent aux systemes SPS est le côut élevé du jeu de barre de l'électricité dans les pays industrialisés. Une vraie comparaison des prix d'électricité devrait inclure les economies secondaires a la non-pollution de l'environment. L'emploi de sessources lunaires pour construire des usines SPS permettrait de réduire les côuts de lancement et d'éviter la pollution par les gaz d'echappement de fusées. Le double avantage pour l'environnement absence de pollution par l'utilisation d'énergie ou par lancement de materiaux de construction permettrait de rendre les SPS viables sur un plan économique.

Introduction

Previous Work

In the early 60's Kraft Ericke proposed transferring energy from point to point on Earth by using microwaves and orbiting reflectors. This concept of redistributing power was also proposed by Buckminster Fuller and that concept is kept alive by an organization called GENIE or Global Energy Network.

Peter Glaser, 1968, proposed using solar arrays in geosynchronous orbit and microwaves to provide energy from space. The first petroleum based energy crisis of the early 70's led to a popular demand for the Satellite Power System (SPS) energy option to be studied. Chris Kraft, then director of NASA Johnson Space Center published an article in 1975 which stated that energy from space might be the rationale needed to justify a sustained human presence in space.

The enthusiasm for energy from space peaked with the expiration of funding for studies in 1980. The results of those studies were presented at a joint DOE/NASA program review. A rebuttal to the findings was issued by the National Research Council, 1981. The baselined system was described in a Boeing study, None of the early work looked at the use of lunar resources.

In 1978 O'Neill proposed building SPS's at his space colonies using lunar resources and an electromagnetic launcher. Woodcock, (1982, 1985, 1986 and 1989) has extensively studied the issue of utilizing extraterrestrial resources. Leonard et al, 1986, looked at the economics of using volatiles from the Martian moons to support space industrialization.

General Dynamics, 1987, and Rockwell, unpublished internal study, have also studied the use of lunar resources to build SPS's. The conclusions generally trend to support the use of lunar resources. The major concerns and unresolved issues are related to: space transportation costs, cost of money, and the ability to produce manufactured products anywhere else other than Earth.

Several issues among the many which were not addressed or ignored were the huge R&D program proposed and the furnishing of new generation capacity in 5 to 10 gigawatt chunks. The 100 billion dollar figure dwarfs the 30 to 50 billion space station Freedom program. At the time the 5 to 10 gigawatt systems were being proposed by NASA the utility industry was choking on new 1,000 megawatt (1 gigawatt) generating units which were just coming on line. However physics, atmospheric interaction and economics drove the system design to such power levels. See the Appendix for more detailed explanation.

A final societal show stopper which was created by the aerospace industry and which is being repeated by the Lunar Power System Coalition is the blyth assumption that society will commit to the marshalling of huge amounts of resources for periods of time range up to 30 years before getting a return on their effort and investment.

Although a wide spectrum of space based generation options such as nuclear and solar thermal were looked at it is the author's opinion based on limitations existing in the global space infrastructure that only the photovoltaic power generation option is viable and amenable to the utilization of lunar resources within the next 20 to 30 years. This is also due in part to the rate at which an industry can draw upon both the financial and technical capital of society to expand itself.

Differences

The key difference between this economic analysis of the use of lunar resources and others is the use a tug/barge vehicle using low thrust, continuously operating nuclear electric ion propulsion (NEP) system for cislunar operations. Although Woodcock, 1989, alludes to ion propulsion by his reference to xexon as a propellant he does not delve into the topic in any great detail. The author's work besides looking at NEP systems considers the use of sulfur as a propellant since it is readily available.

Resources

The selection of resources should be driven by cost/benefit analysis. This will make the design of second or third generation SPS systems materials driven rather than theoretically driven. An example is the use of lunar aluminum or titanium rather than Earth derived graphite structural members with a low coefficient of thermal expansion.

We can postulate resource development moving from lunar oxygen and sulfur to simple structural elements and eventually solar cells. Wiring will, because of the lack of insulating materials, not be produced on the lunar surface for a long time.

Development

The development of resources will probably be driven by a combination of economics and necessity. This leads to assuming that lunar oxygen for life support and propellant along with bulk building materials for shielding will be among the first products produced. Metals and/or solar cells will probably be next. The choice will depend upon levels of automation and compexity of processing as well as packaging for shippment. Solar cells being more dense than metal tubing may be easier to ship off the Moon. A point worth noting is that terrestrial designs for light weight arrays may not be practical, i.e. cost effective, when the arrays are made from lunar derived components. Again the materials used for making light weight arrays may not be available.

Possible Systems (Mission Architectures)

All Chemical

Chemical, moderate thrust (compared to nuclear), rockets with aerobraking for Earth return are the most popular systems and the most studied by NASA. While fast and probably suitable for manned missions they are expensive to use and operate for resource development. There are many studies on the use of chemical rockets. While this is the technological simplist solution it, as will be shown, is the most expensive.

Chemical/Nuclear/Chemical

The system which will be analyzed and discussed in this paper is based on the use of chemical rockets to launch material from Earth to LEO or more precisely a 500 to 900 km

nuclear safe orbit. Nuclear electric propulsion is used to move material from LEO to GEO for the Earth resource case or to a lunar parking orbit where cargo modules are transferred to a chemical or nuclear rocket acting as a space age lighter for the lunar resource case.

Earth to LEO performance data, i.e. 250 to 500 km, is used without modifying the delta v's needed for for the higher "nuclear safe" orbital height of 900 km. Lunar oxygen is assumed available for the lightering operation. Initial deployment of the resource facility is accomplished using a nuclear electric system based on the SP-100 nuclear power system and xexon for a propellant. Cargo operations are based on a second generation power system and the use of lunar sulfur as a propellant for the ion thrusters.

Keaton, 1986, describes some of the advantages of that nuclear electric propulsion (NEP) transportation systems have over chemical and nuclear thermal systems. The advantages accure mostly to shipping materials which can tolerate longer times within radiation fields such as the Van Allen Belt in order to realize savings in the propellant mass needed to move them from LEO to GEO or from the Moon to GEO.

ElectroMagnetic Launchers

Electromagnetic launchers or rail guns to use the modern defense department terminology have been proposed for use in launching materials for both the Earth and the Moon. An electromagnetic launcher located on the west side of the Andes pointing east could dramatically reduce launch cost for small volume packages that could withstand the accelerations. EM launchers on the Moon face the same constraints. Both systems while technically feasible are, given the current small volume, economically infeasible.

While the use of electromagnetic launchers may be technically optimum and, if the industrial infrastructure was in place on the Moon to build them, economically competitive they are not viable option for the near term project which must be profitable in a fairly short time frame.

Launch Cost Assumptions

Currant Launch Costs to LEO

Table 1 lists a set of costs for different types of launchers as well as projections. The projections are based on data contained in the 1975 Boeing SPS system study. The costs were escalated to 1986 dollars. The details are explained in Leonard, 1990.

Table 1 - Current Launch Costs (1986 $)

Launch Vehicle	Cost	Cost per kg
Shuttle	150. million	$5,080.
Titan IV	250. million	$13,160.
Ariane		
Proton	20. million	1,053.
Long March 3		

Based on costs, commitment and availability of launch resources it is the author's opinion that the development of lunar resources will have to depend on launch services furnished by an entity other than NASA. Consequently I will base part of my economic analysis on using a launch system such as the Proton and a cost to LEO of $1,000. per kilogram of payload.

Projected Launch Costs to LEO

A minimum, i.e. lower bound, launch cost can be developed by ignoring such major cost elements as operations and cost recovery for ground facilities. The usefulness of such an unrealistically low cost is that it establishes a lower bound against unrealistic claims by proponents of power from space. The derivation is based on the manufacturing costs of aerospace systems. The basic cost data was taken from a mid 1970's Boeing study done for the SPS program. Details on the derivation of the lower cost bound are given in Leonard, 1991 and Leonard et al, 1987. The costs are 1986 dollars per kilogram.

Table 2 - Projected **Minimum** Launch Costs

Cost Basis	Expendable	Re-useable
747	792.	27.30
Saturn IC	1,474.	39.20
B-1	4,070.	85.20
Saturn IVB	4,679.	93.80
Apollo	20,970.	384.30

Launch costs for a mature construction program will be based on either 800 dollars or 100 dollars per kilogram of payload.

Balance of Transportation System

CisLunar Transportation System

Most economic analyses of the use of lunar resources have ignore the freighter or tug and barge concept of moving large masses. Leonard et al, 1986, looked at the use of a system of nuclear electric tugs and barges in their analysis of the economics of mining the Martian moons for volatiles. This work which was based on a paper on low-thrust rocket trajectories by Keaton, 1986, showed that by using tugs and locating fuel at transportation nodes that mining the Martian moons could be economical if there was a large enough demand, i.e. requirements for hydrogen on the order of thousands of tons a year. The concepts are extended to looking at a resource supply operation operating between the Moon and Earth's geosynchronous orbit.

An alternative, especially for moving cargo, to impulse thrust systems is a low thrust, continuously operating propulsion system. A variety of such systems have been discussed in the literature, Keaton, 1986.

Although there are a variety of near term propulsion possibilities proposed I limit myself to electric ion propulsion for this study. NEP technology, Clark (1974), Jones (1984), and Hord (1985), is well established and its performance well documented, at least in the laboratory.

Moon to Low Lunar Orbit

Woodcock, 1989, reports on the results of a parametric study of lunar resources. In that paper he lists the following delta v's in meters per second and masses in metric tons.

Table 3 Transportation Basis for Analysis

Transit	delta v (m/sec)	Propellant (metric tons)	Payload (metric tons)
LEO/GEO	4,200.	4,320.	1,870.
LEO/LLO	4,000.	496.	153.
LLO/LS	2,100.	124.	153.
LS/LLO	2,000.	121.	71.
L2/GEO	2,500.	1,970.	48,000.

Not analyzed in this study is the case involving a manufacturing facility at L2, Woodcock, 1989, and its interaction with materials or assembly operations in highly eccentric Earth orbits, Lewis, 1991.

Methodology

The underlying methodology of this economic analyses of the use of lunar resources was derived by Keaton, 1986, for low thrust trajectories. A precursor paper by Keaton, 1985, discusses the benefits of transportation nodes. These concepts were used by Leonard et al, 1986, in analysis of the economics of developing the volatile resources of the Martian moons.

Keaton, 1986, expresses the initial mass of the transfer system as:

$$m_i = m_l + m_w + m_p + m_s \quad \text{Where}$$

m_l = payload mass
m_w = power supply mass
m_p = propellant mass
m_s = structure mass, assumed to be $0.1 * m_l$

The final mass, m_f, is :

$$m_f = m_i - m_p$$

Design Equations

Keaton, 1986, derived a set of equations which can be used with delta v's and mission times to optimize a transportation system and suggested an evolutionary development for nuclear electric powered (NEP) vehicles. This evolutionary program can be used to define a development program for space nuclear power supplies. Those equations are listed below. γ is a dimensionless parameter which is the square root of the integral of the acceleration function over the trip time.

$$\frac{1}{m_f} = \frac{1}{m_i} + \frac{\gamma^2}{m_w}$$

γ can also be written as $f\frac{\blacktriangle v}{V_c}$ where $\blacktriangle v$ is the velocity change needed for a given mission and V_c is the characteristic velocity and is defined by

$$V_c = \left(\frac{2T}{\alpha}\right)^{\frac{1}{2}}$$

Where T is trip duration in seconds and α is specific power kilograms per watts.

$$\frac{m_w}{m_i} = \gamma - \gamma^2$$

$$\frac{m_l + m_s}{m_i} = (1 - \gamma)^2$$

$$\frac{m_P}{m_i} = \gamma$$

Example

The example is taken from Keaton, 1986, and involves moving 200 metric tons of payload from LEO (500 km circular altitude orbit) to GEO (approximately 32,000 km altitude orbit). The following values are given:

$\blacktriangle$v = 5 km/sec
T = 1 month (2.6 x 10^6 seconds)
α = 10 kg/kW_e or 0.01 kg/W_e

$$V_c = \left[\frac{2(2.6 \times 10^6)}{0.01}\right]^{\frac{1}{2}}$$
$$= 22.77 \times 10^3 \text{ m/s}$$

$$\gamma = \frac{5.0}{22.77} = 0.2196$$

$$\frac{m_w}{m_i} = 0.22 - 0.22^2 = 0.17$$

Initial mass

$$\frac{m_l + m_s}{m_i} = (1 - 0.22)^2 = 0.61$$
$$\frac{m_l}{m_i} + \frac{0.1 m_i}{m_i} =$$
$$m_i = \frac{200}{0.51} = 392. \text{ metric tons}$$

Propellant

$$\frac{m_P}{m_i} = \gamma = 0.22$$
$$m_P = 0.22 m_i = 86.2 \text{ metric tons}$$

Power supply

$$m_w = 0.17(392) = 66.7 \text{ metric tons}$$

Check
200. + 86.2 + 66.7 + 39.2 = 392.1

Cost of Propellant vs Cost of System

Keaton, 1986, states that the smaller we make γ the smaller the amount of propellant needed for a given mission. However minimizing γ requires more power delivered to the exhaust stream and hence a larger, i.e. more massive, power supply. The economic analysis or trade study involves minimizing the sum of the cost of the propellant and the cost of the system, which is in reality the cost of capital per trip. Propellant cost is a function of either the Earth to LEO launch cost for a optimum thruster propellant such as argon or xexon or the cost of manufacturing a non-optimum propellant such as oxygen or sulfur. System cost is the combination of first cost, cost of equipment and the launch costs associated with placing the transfer tug and barge in LEO. Since we have included propellant costs as a separate line item and as will be seen this costs dominates the operating costs we will for this first order approximation assume propellant costs equal operating costs.

Economic Assumptions

Cost of Money is assumed to be 12 percent.

Capital Recovery for NEP systems is assumed to be 10 years and for the SPS power systems the time for recovery is 25 years. The equation used for capital recovery is given below and was taken from Grant and Ireson, 1970.

$$CAP = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Where i is the interest rate and n is the number of years.

Table 4 - Capital Recovery Factors

Interest	Time Period	Cap Rec Factor
12 %	10	0.177
12 %	25	0.128

The above factors times the amount financed or the cost of the project gives the yearly cash flow needed to recovery the capital cost of the project. This cash flow does not include operating costs, taxes and profit.

Rate of Growth

A factor often overlooked in these sort of analyses is how much money can the economy

furnish to a given enterprise and at what rate, i.e. cash flow as opposed to interest rate. Although some consumer electronics companies have grown at the rate of 30 percent this is fairly unusual especially for heavy industry. A good historical comparison would be the growth rate for the nuclear power industry. One difference would be that SPS seems to have to fight an uphill fight for acceptance whereas nuclear power in its infancy had the full support of governments. Another factor to consider is that startup capital for a computer company is much less than that proposed for the SPS venture.

Recent examples such as the Alaska pipeline and the Cunnel indicate that for projects with a very high revenue potential and/or strong government support start up capital on the order of 4 to 15 billion can be accumulated. An important factor to keep in mind is that these are projects which will start producing revenue almost as soon as they are finished. There is little or no market uncertainty. The startup capital comes from either equity (stockholder's investment, i.e. conversion of savings to risk taking), borrowing or internally generated cash, i.e. profits.

A reasonable rate of economic growth which would be based on earnings from systems built with mature technology is probably on the order of 5 tyo 10 percent baring any new "energy crises". Any faster growth would probably have to come frm government subsidies and result in a diversion of money from either social or defense programs.

Technical Assumptions

Specific Impulse of Ion Thrusters

The impluse of ion thrusters is taken to range between 3,000 and 5,000 with some systems being projected to reach 10,000.

Power densities

P(t) = amount of power delivered to exhaust material and Pa = total power of the system. $P(t) = \varepsilon * P(a)$ where ε is efficiency of power conversion. Conversion efficiency for thermo-electrical systems (RTG's) is approximately 4.5 %, i.e. SP-100, for thermionic systems such as the Soviet's Topaz II the efficiency is around 9 to 11%, and for dynamic systems the efficiency is approximately 33%.

The mass of the power system is given by mw $= \alpha * P_a$ where α is the specific mass of the power supply in kg/kW_e. Newkirk et al, 1990, discusses scaling the SP-100 power system up to 40 MWe. The average mass per KWe is approximately 1kg/KWe for the nuclear subsystem and 10kg/KWe for the total power system. Others, Barnett, 1990, and report on the weight to power ratio as being between 6 and 8 kg/KWe. We will use the value of 8 kg/KWe for second generation systems. Isenberg and Heller, 1989, list a specific weight of 25 kg/KWe for the SP-100. This weight will be used for first generation systems having power levels up to a megawatt.

Economic Analysis

The costs will be developed based upon 100 metric ton payloads. The costs can then be easily scaled by the reader.

Cost of Earth based system

Earth to LEO: launch services are assumed to be \$1,000 for cases 1 through 3 and \$500 dollars per killogram for cases 4 through 9.

LEO to GEO: transportation is based on nuclear electric systems. Cases 1A, 4A and 7A establish a baseline for comparison. They are based on the assumption that all material including the propellant for nuclear electric propulsion comes from Earth. The following table lists transportation costs to GEO as a function of trip time.

Trip time days	Earth/LEO ($/kg)	LEO/GEO ($/kg)	Total ($/kg)
10	$1,000	$3,509	$4,509
15	$1,000	$1,701	$2,701
20	$1,000	$1,159	$2,159
25	$1,000	$899	$1,899
30	$1,000	$746	$1,746
35	$1,000	$645	$1,645
40	$1,000	$573	$1,573
45	$1,000	$519	$1,519
50	$1,000	$477	$1,477
55	$1,000	$443	$1,443
60	$1,000	$415	$1,415

Cost of Lunar based system

Cost of Materials: , i.e the cost of the facility on the Moon, will approximately be equal to the cost of transportation. This cost has three components: Earth to LEO, LEO to LLO, and LLO to the surface of the moon.

CisLunar or LEO/LLO and to the surface costs are listed in the following table using the assumptions of cases 1 through 3.

Trip time days	LEO/LLO (\$/kg)	LLO/surface (\$/kg)	Total (\$/kg)
10	\$2,861	\$2,319	\$6,180
15	\$1,479	\$1,198	\$3,677
20	\$1,031	\$836	\$2,867
25	\$810	\$657	\$2,467
30	\$678	\$549	\$2,227
35	\$589	\$477	\$2,066
40	\$525	\$426	\$1,951
45	\$477	\$387	\$1,864
50	\$440	\$356	\$1,796
55	\$410	\$332	\$1,741
60	\$385	\$312	\$1,696

Cost of Lunar Manufacturing Plant was developed using the transportation costs shown above. Product cost was determined by taking total cost times the capital recovery factor and dividing the result by plant output. Product costs are listed in the appendices to this paper. They can be obtained from the author at no cost.

Cost of Transportation to GEO: is the sum of the cost of getting the material off of the lunar surface to waiting NEP freighter and then moving it to GEO.

The analysis showed that if all material including propellant needed for lunar surface to LLO and LLO to GEO had to come from Earth that the lunar resouce alternative was not economically feasible by at least an order of magnitude. Using a lunar resource based propellant system for surface to LLO operations the lunar resource option becomes cost competitive. Using lunar materials for both surface and Cislunar operations the lunar resource alternative is more cost effective than a 100% Earth based approach.

Cost of Power: In the end it all comes down to the cost of power in cents per kilowatt hour. A minimum or lower bound cost is derived from the capital recovery factor times the cost of the plant times the plant capacity divided by number of hours of operation per year. The cost per kw-hr is shown in the two figures for the various cases analyzed.

Context Previous Mega-Projects

Panama Canal cost about 375 million in 1907 dollars over 7 years and pushed the frontiers of both construction and medicine.

TVA is an example of the government developing the infrastructure needed by both industry and the individual.

Manhattan Project cost estimates range from 1 to 2 billion in 1943 dollars. This project was also built during a major war effort. If this project shows us anything it is that developing lunar resources for providing energy from space is a much less daunting undertaking from both an economic standpoint and access to available resources today than making the bomb was in 1945.

Apollo was a fluke in megaprojects in that it occurred just as the technological infrastructure was ripe to give birth to a major thrust and it had the backing of a charismatic President. While it brought glory to American technology it also established a bad paradigm for attempting new space projects. It did demonstrate the advantages in such disparte areas as science and foreign policy to being a world leader in space. It also established a baseline for spending for a space project that has the strong and active support of the Presidency and the people.

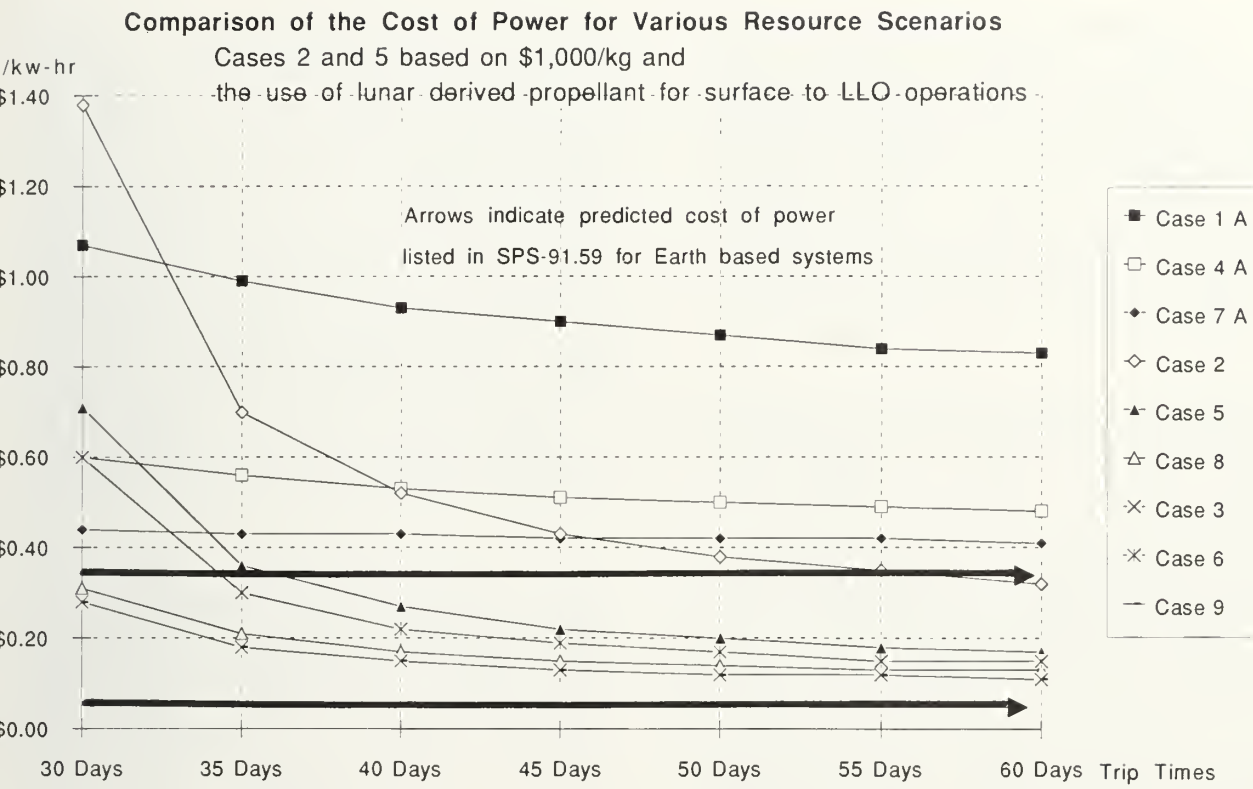
Interstate Highway System is a 150 billion plus project which spans 50 states and 40 years. It is an infrastructure project which provided tangible returns to the people in the form of faster and easier travel in its first year of construction. One can raise the question whether the nation would have spent 150 billion dollars if they had had to wait 40 years before they could drive on the new highways.

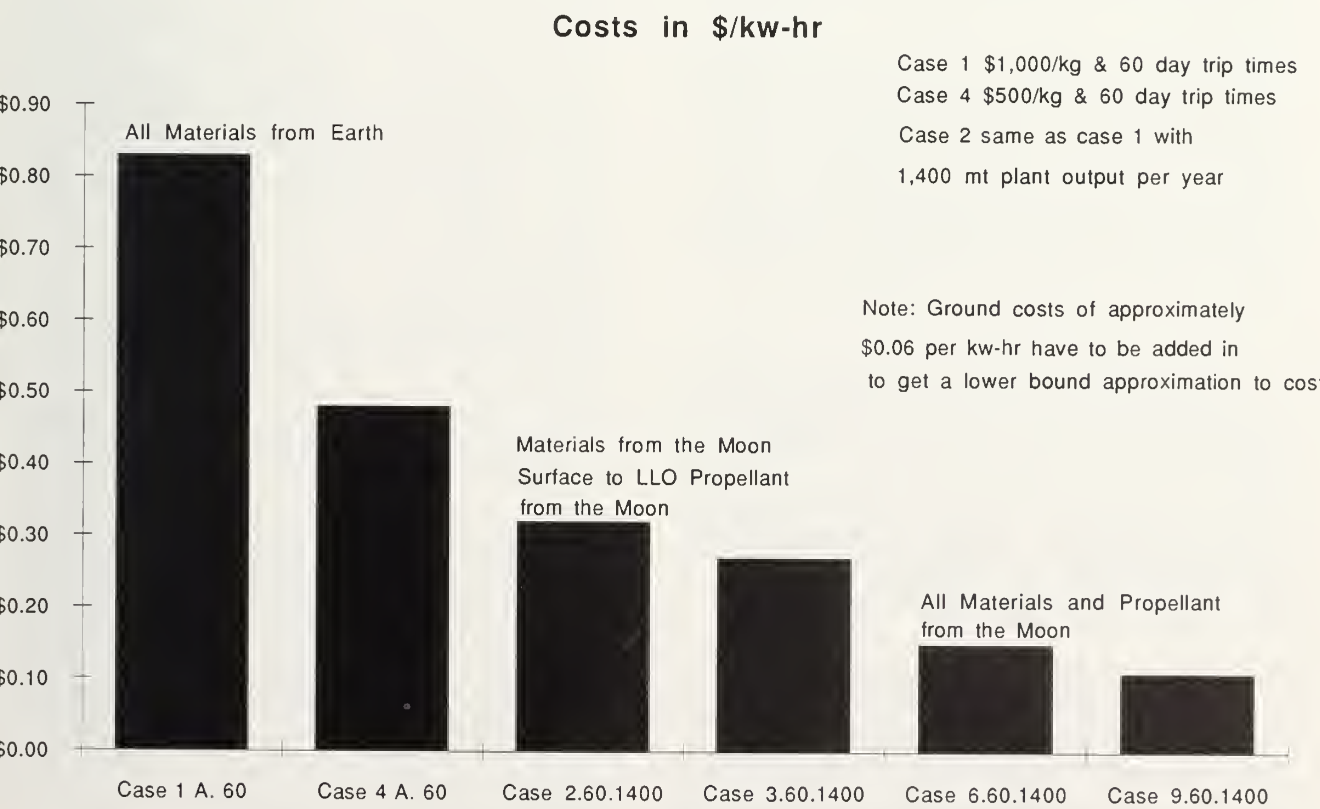
Alaska Pipeline demonstrated the co-operative behavior between supposedly competing oil companies. It also demonstrated a new level in project financing and manage-ment techniques. The construction industry again demonstrated it could work in extreme and hostile environments in remote locations.

Cunnel demonstrates as has multinational development of fighters and supersonic transports that nations can work together economically and produce useful, revenue producing products and projects. At an estimated 12 billion dollars it also establishes a new benchmark for financing infrastructure development.

Nuclear Power Systems at least in the US demonstrate that there are cost limits, schedule limits and public acceptance limits to the implementation of new technology within the utility industry.

Conclusions about mega projects can be drawn from the above examples.





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Summary and Conclusions

Based on costs, commitment and availability of launch resources it is the author's opinion that SPS logistics support from Earth to LEO will have to depend on launch services furnished by an entity other than NASA. If the Soviet space program holds together under the strain of economic reform their launch capabilities, i.e. PROTON and ENERGIA, and costs, seem to match near term needs.

Furthermore, given that the necessary technology is known by a number of nations and the basic cost of materials is fairly constant the competitive edge in providing launch vehicles will lie with the nation that can provide the lowest cost combination of vehicle, launch services and reliability. A question which needs to addressed is what is the level of reliability needed at what cost for launching construction materials rather than humans or high value communication satellites.

On a straight standard of living and salary basis the rank ordering in terms of increasing costs is: the PRC, the Soviet Union, Japan or Europe and finally the US. Existing demonstrated technological ability favors the USSR over the PRC while economic stability favors either Japan or Europe over the USSR even though costs might be higher. It is the author's opinion that high costs and a monopolistic government operation rule the US out of the running in providing launch services for the commodities needed to establish a lunar resource utilization operation.

It appears that at the current time only two nations, the US and the USSR, have the technological infrastructure to deploy the space nuclear power assets needed to support the heavy haul Earth to LEO and cislunar operations need to establish a lunar resource utilization operation. Whether they have the will or the economic stability to do so is a question for much debate.

The evolutionary development of an international space program designed to benefit mankind will require a transportation fleet that can move large masses economically into and out of gravitational wells. While the use of such vehicles should be in the domain of private enterprise the development of the NEP freighters and barges of the 21st century should be viewed as a societal cost similar to the interstate highway system or the development of airports.

In summary the following conclusions can be drawn from this first order analysis. The use of lunar resources will be cost competitive if those resources can be returned to GEO by using lunar derive propellants. The lunar resource facility will have to have an annual capacity in excess of 1,000 metric tons of saleable products. Costs and development scenarios indicate that lunar oxygen should probably be the first product followed by sulfur or aluminum for use in a solid propellant rocket for surface to LLO operations. The next product would probably be propellant for the ion thrusters used on the LLO to GEO route. Also being able to refuel the construction transports operating on the LEO to LLO route at LLO would reduce construction costs.

Finally the plant output would include solar cells as a high mass, high value product. These cells will different greatly from terrestrial cells in that the economics and the launch environments will differ drastically. Structural products such as tubing and electronic components will require more infrastructure and in the case of the former depend on designs which accomodate the constraints imposed by the space environment.

Power requirements range from a high of 1.25 Megawatts electric for the LEO to GEO route to a low of 0.70 megawatts for the LLO to GEO route. Changing the specific power of the NEP power supply from 0.25 kg/watt to 0.008 kg/watt reduces power requirements to 0.61 MWe and 0.34 MWe.

The cost of power from SPS's built from lunar materials will be above the 15 to 30 cents per kw-hr shown in the figures. In addition to profits, operating costs there must be added the cost of the receiver which will run about 6 to 8 cents per kw-hr. The development time frame for a lunar resource approach is probably on the same order of magnitude needed to achieve very low launch costs and light weight low cost solar cells here on Earth. If true costs of power including environmental impacts are factored into all sources of power generation it is the author's opinion that energy from space derived from lunar resouces will be economically competitive with current generation methods. Whether energy from space can win in the political circles will depend on the honesty of our investigations, the knowledge of the public and strength of special interest lobbies.

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Related Work

This paper is one of four presented at the SPS 91 Conference. Their relationship is described below. Together they describe a vision for the future and a reasonable path which may be taken to transform that vision into reality

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SPS 91

A3.3 The Moon as a source of energy for terrestrial use

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ABSTRACT

^{3}He may be obtained from the surface of Earth's moon to fuel terrestrial power reactors supplying 200 GW_e to the Earth's electrical power grids by 2050. Gaseous and metallic co-products create a lunar industrial complex producing commodities and manufactured items. Near self-sufficiency of the lunar community will be achieved early in this scenario. Up to 170,000 tons may be placed into lunar orbit to establish and maintain 50 mines/manufacturing centers, and about 2,800 persons may be employed on the moon. Reduction of space transportation and personnel by system improvements will enhance the attractiveness of this option for power from space.

RESUME

Le sol lunaire peut fournir de l'hélium 3 à des réacteurs de fusion sur Terre produisant 200 Gwel en 2050. Les sous-produits d'extraction alimentent un complexe lunaire d'industries manufacturières. La quasi-autonomie de la communauté lunaire peut être réalisée rapidement. 170 000 tonnes sont amenées sur la lune pour créer et entretenir 50 centres miniers et manufacturiers, tandis que 2 800 personnes y travaillent. Ce scénario peut être amélioré.

Introduction

Dr. Gerald Kulsinski and his associates of the University of Wisconsin suggest[3,7] the helium 3/deuterium (^{3}He/D) fusion reaction is superior to the current fusion research path of using deuterium/tritium (D/T) cycle, as this choice of fuels alleviates the high energy neutron bombardment of reactor structural elements.

Two problems now appear to inhibit this fuel cycle from becoming more acceptable: First, the time-temperature product necessary to obtain the fusion reaction is higher for the ^{3}He/D cycle than for the D/T cycle. This is expected to add a few years to achieve energy break-even in the research program, in which the goal is to obtain more energy through fusion reaction than is invested in obtaining the conditions for fusion to occur. A metric ton of the ^{3}He fuel, along with D available from sea water, can produce 14 to 19 GW_e-years of electrical power.[3,7]

Second, the availability of ^{3}He on Earth is limited: only 17 kilograms per year from natural gas and decay of tritium in thermonuclear weapons. Dr. Kulsinski and his associates reviewed the Apollo lunar sample data and concluded the Earth's moon is a good source of this otherwise rare fuel, as gases of the solar wind, including hydrogen, carbon-bearing gases, nitrogen, and helium in both its forms, has been trapped for eons on the fine-grained lunar material near the surface. These gases may be evolved from the solid material by heating the lunar material.

In characterizing the future attractiveness of this source of baseload energy for Earth, an understanding of several first-order issues and "figures-of-merit" is required. First, can the fusion reactor become an attractive power source? Second, can the use of the ^{3}He/D cycle be reduced to practice within a reasonable time after obtaining break-even with the D/T cycle? Both of these issues are out-of-scope of this paper. Should either of these barriers prove to be insurmountable, other options for supplying space energy for Earth needing similar lunar infra-structure are available: the *Solar Power Satellite*, built largely from lunar materials, and the *Lunar Power System* which places power collection and microwave transmission equipment on the surface of the moon.

Third, what abundance of ^{3}He can be located on the moon? Fourth, in what total quantities? The answers to these questions will determine the amount of lunar material which must be mined and processed by heating to release the trapped volatiles and if the resource is sufficiently extensive to warrant an investment.

Additional questions relate to the cost of acquiring the commodity on Earth: What are the costs and timing to establish and operate mining and manufacturing complexes on the moon and to provide the round-trip transportation to these locations? This paper reviews the relevant literature to address the availability and infra-structure issues, but will not provide cost and schedule estimates. Instead, early precursors of cost estimation will be derived: mass delivered from the Earth to orbits of the moon and the number of people working on the moon to produce ^{3}He at the desired rate.

Objectives

The objectives of this paper are to examine a scenario for the delivery of ^3He to Earth in terms of:

a. Mass needed to be placed on the moon and other space locations.

b. Numbers of people needed in space.

A ^3He production scenario is adopted which builds to 15 tons per year of ^3He delivered to Earth during the interval 2010-2050 and sustains this rate during the interval 2051-2070. The paper examines the extent of activities needed for obtaining ^3He from the moon, estimating time histories of the:

1. Nature and mass of the equipment complex which will evolve on the moon.

2. Staffing needs of the several facilities needed to operate and maintain these largely robotic lunar resource bases.

3. Space flight rates between low lunar orbit (LLO) and the lunar surface bases (LSB) and mass to be delivered to LLO from Earth.

4. Degree of self-sufficiency of the lunar enterprise and the extent of re-supply from Earth which appears to be necessary.

5. Net available product stream produced by this lunar industrial complex which can be made available to benefit other uses (beyond this present scenario) such as:

   a. Supply of lunar-derived propellants for Lunar Transport Vehicles (LTVs) ferrying people and supplies between low Earth orbit and orbits in the vicinity of the moon.

   b. Missions to Mars.

   c. Additional expansion of human presence in space, including the lunar surface.

Amount of ^3He Required

To size the elements of the scenario, it is necessary to know how much ^3He is required. Kulsinski uses 19 MW_e years of deliverable electrical energy per kilogram of ^3He. Woodcock derives[8] the number used by several other investigators: 10 MW_e years per kg. The difference is explained by different forecasts of fusion plant efficiency. **We will use the value: 13 MW_e years per kg. of ^3He. Thus, for this scenario, 200 GW_e years per year of electrical power delivered to the power grid by the year 2050, 15 metric tons per year of the product must be delivered to Earth** during the interval 2050 to 2070, with lesser amounts delivered beginning in 2010.

Assumed Helium 3 Abundance

Examination of specimens returned from the moon by Apollo astronauts indicates that ^3He is present in weight parts per billion (wtppb) quantities in the upper 3 meters of the lunar regolith. The issues are (a.) what concentrations can be obtained from favorable locations identified by future exploration and (b.) how much of that can be successfully removed. Early ^3He systems analyses were conducted using 7 to 9 weight parts per billion[7,8]. A recent paper (Cameron)[4] suggests 7 to 18 wtppb is available from the 85,000 km^2 northeastern portion of Mare Tranquillitatis. The regolith of this region has a high titanium dioxide content, an indicator of high volatiles concentration, including ^3He. Dr. Cameron estimates availability of 9,400 tons of ^3He in minable regolith. This indicates a supply adequate to serve the electrical power needs of the United States at the year 2050 level for 63 years in this one region.

An estimate of 20 wt ppb 3He will be used as the concentration of ^3He present in the regolith to be mined, available to a depth of 3 meters, more optimistic than Cameron's estimates, assuming selection of more favorable mining areas found by future exploration efforts.

The concentration of volatiles tends to increase with decreasing particle size. There is an advantage to segregating the regolith mined by size, investing thermal process equipment and energy into only the richer, smaller, size fractions. The University of Wisconsin concept[4] assumed that 55% of the regolith would be discarded before processing, still producing 8.9 wtppb of ^3He of the 9 wtppb total of the original material. **For this paper, we will make the assumption that 50% of the regolith mined is heated, and no ^3He or other volatile gases are discarded with the coarse regolith fraction.**

The next issue is how much of the ^3He and other volatiles present may be recovered and stored for use. The first determinant of this factor is the temperature to which the regolith is heated. Simonds[3] selected 927 ^oC, the upper limit of Inconel reactor pressure vessels, releasing 80% or more of the trapped volatiles. Dr. Kulsinski cites Pepin, 1970, indicating 98% release at 927 ^oC. **This paper will assume that 75% of the volatiles content is recovered, therefore 15 wt ppb of ^3He is recovered, based upon total regolith mined, or 30 wt ppb recovered from the regolith thermally processed.**

^3He is only a small fraction of the volatile substances released by thermal processing. Table I presents estimates of other gases produced (co-products) as multiples of the ^3He produced. Processing of the solid material heated to release the gases may produce additional oxygen and useful solid materials.

Mining & Processing Equipment

To extract 15 mt of ^3He per year, the mature mining operation will mine 1 billion tons per year of lunar regolith and thermally process 500 million tons per year, a formidable but not unprecedented scale of mining and process operations. **Standard mines/ manufacturing plants capable of mining 20 million tons per year each will be established in favorable locations**, such as the northeastern part of Mare Tranquillitatis. At maturity, 50 such mines will be in simultaneous operation, each equipped with mining and processing equipment and each staffed with the minimum required human crew to provide maintenance, troubleshooting, and repair for the operation to be telerobotically operated from Earth. The deliverable product of each mine will be 300 kg of ^3He per year, or 25 kg per Earth month. This seems a trivial amount of product for such a large effort, but the product of each mine will fuel about 4,000 MW_e of electrical power generation, enough for a medium size city.

Each mine will also produce volatile gases consisting of 930 tons per year of ordinary helium, 1830 tons of hydrogen, 990 tons of water, 570 tons of carbon monoxide, 510 tons of carbon dioxide, 480 tons of methane, and 150 tons of nitrogen, for a total gaseous product stream of about 15 tons per Earth day. Concurrent production of oxygen by the reduction of a portion of the hot solids in the gas release reactor can produce additional oxygen, along with large quantities of iron, glass, cast basalt, and, with additional difficulty, titanium, aluminum, silicon, and other needed materials.

Various assumptions and estimates have been made on the makeup and mass of equipment needed by a mine to perform this work. Igor Sviatoslavsky identified[3] a conceptual mobile mining/processing machine capable of mining 5 million tons per year and producing 33 kg per year of ^3He. This miner has a mass of 18 tons and requires 200 kW_e plus solar energy for process heat. This approach requires an estimated 1064 tons of equipment per ton of ^3He produced per year; including about 540 tons for mobile miners, 524 tons for process and power, plus 258 tons for the "base camp".

Gibson[7] reports on a study by R.E. Gertsch to recover hydrogen, estimating a miner mass of 30 tons to recover 117 tons of H_2 per year. Using a $H_2/^3He$ ratio of 6100, this is equivalent to a mining and processing equipment mass of 1564 tons of equipment per ton of ^3He/year, not including human support (base camp).

Simonds[3] estimated the equipment mass and energy needs for a combined gas recovery and ilmenite reduction plant to produce a relatively modest product stream of 14 tons/yr. of H_2 and 96 tons/yr. of O_2 by mining 352,000 tons per year of regolith. This plant has total mass, including a 1.8 MW_e nuclear power supply, of 62.4 tons. At the 6100:1 $H_2/^3He$ ratio, this plant produces 2.3 kg per year of ^3He, and has a specific mass of 12,000 tons/ton ^3He/yr without crew facilities. Using the richer soil and the "gas classifier" suggested but not used by Simonds[3], using the same amount of material mined, but not heating the coarser 50% of the material, reduced the specific mass to 10,000 tons/ton ^3He/yr.

This last set of data was scaled up to a 20 million ton/year standard, fixed location mine, producing 300 kg of ^3He per year, with economies of scale including a reduction of the specific mass of a nuclear-electric power supply and 15% rather than 30% mass margin. Total equipment mass of 1930 tons is indicated, including a 30 MW_e nuclear powerplant. This produces a specific mass of 6,400 tons/ton ^3He/yr. for mining and processing. This is higher than the design to recover only ^3He offered by the University of Wisconsin group, in part because it is designed to collect and process more diverse materials.

The range in these estimates of specific mass of equipment on the moon to produce ^3He is from 1,100 to 6,400 tons per ton ^3He per year, not including mass to support the human staff. More work is needed by the mining, construction, chemical processing and space systems engineering communities, including bench tests and other empirical work, to reduce this uncertainty.

This report will use the higher equipment mass of 6,400 tons per ton per year of ^3He, not including habitats, as representative of a fully integrated, centralized, lunar regolith processing facility. This plant mass might be reduced, but can, with present estimates, produce many times its mass in total products each year.

In addition to new equipment delivered to the moon to fulfill the scenario, spare parts and consumable supplies will be needed to keep it functional. With the remote location of the equipment, it will be necessary to overhaul and refurbish equipment to the maximum extent possible. For the purposes of this analysis, **it is assumed that the basic equipment has, with servicing, lifetime beyond the horizon of the scenario.**

A model for the delivery of replacement parts as a function of equipment age was examined. The first year of operations was estimated to require 1½% of equipment mass to reverse "infant mortality" failures. Years 2 through 5 operated smoothly with ½% per year replacements. Parts consumption then grew to 5% per year in year 10. The restored unit repeated this cycle every ten years. The average of this schedule is 1.75% per year of operational equipment mass, thus **spare parts and servicing consumables require additional mass provided from either Earth or lunar factories of 1.75% per year of the then-present total equipment inventory.**

As collection and processing of the lunar materials required for gathering ^3He will permit and require a significant lunar infra-structure and population, it will be possible at small marginal cost to recover and utilize a portion of the metals (iron, titanium, and

aluminum) and other commodities which can be produced. It is assumed that spares, as well as new **equipment will be manufactured on the moon beginning in 2025**, at an annual growth rate of 2 percent of the mass required for new equipment and spare parts per year, **attaining 90% self-sufficiency** soon after all of the equipment is in place.

To improve this scenario, future work should address means of using native materials earlier to provide commodities and manufactured products made from lunar materials, displacing some of the Earth re-supply.

Equipment mass, electrical and thermal power, housing, and personnel will also be needed at the lunar bases to manufacture equipment parts, refurbish spare parts on the moon, and provide other items such as gases, building materials and simple shapes such as tubing for radiator panels. These people and this equipment are assumed to be included within the uncertainties of the much larger mining and processing requirements.

Staffing of the Lunar Facilities

Support of humans on the moon will constitute a major cost of the lunar activities. Their periodic replacement and rotation back to Earth can be a major impact on space transportation systems. The size of staff to operate the mining and manufacturing complexes on the moon must be minimized by application of remote control from Earth, robotics, artificial intelligence, telepresence, virtual reality, and other means of increasing the productivity of remote activities.

Even with full application of these technologies, people will have to be on the scene to provide the first-hand observations, diagnoses, and delicate or unplanned manipulations which cannot be provided by machines or remote operators. As the nature and extent of the equipment required for a mine/manufacturing complex are yet poorly understood, so are staff size estimates. Their numbers may be determined more by skills mix and the extent of continuous operation than by workload.

A representative Standard Lunar Mine staffing plan based upon a skills mix approach and 24 hour per Earth day operations was examined. The staffing model increases staffing during the 8 to 10 Earth-day "lunar midday" interval when mining and processing intensity is at a maximum and diverts production staff to equipment maintenance and other tasks during lunar night when the volatile materials are cooled and separated.

Three Departments are identified: Operations Department, Support Department and Maintenance Department. Operations includes Excavation, Surface Transport, Processing and Storage Sections. These people assist the primary system operators (located on Earth, operating the facilities telerobotically), providing on-site eyes and hands to supplement pre-programmed activities.

The Support Department includes Food Service, Supply, Facilities and Transport Sections. These people support their fellow crew members on the moon. One or more is a Medical Doctor.

The Maintenance Department includes Electrical, Mechanical, Avionics and Fluids Systems Sections. These people assist Earth maintenance staffs in trouble-shooting, remove and replace dysfunctional parts, load used parts into fully automatic equipment refurbishment tools and place refurbished parts into stores when fully checked out by the automatic equipment. Each Department has a Director and Assistant Director trained in all skills of the Department. Overall activities are managed by a Site Director and Deputy. **Total staffing of the Standard Lunar Mine is 56 persons** for a 20 million metric tons per year mine processing 10 million tons per year.

Space Transportation Near the Moon

Transportation of goods and people from Earth to the moon and return will be a primary contributor to both investment and operational activities and hence costs of any ^{3}He mining scenario. Three distinct space transportation elements will be needed: (a.) space launch services, with vehicles large enough to place several hundred tons of useful payload into low Earth orbit (b.) cislunar orbit transfer capability, either nuclear or solar powered electric propulsion systems, for efficient transport of large cargo; and chemical propulsion, fast trip time rocket vehicles for transporting people to lunar orbit and return them to Earth and (c.) chemical rocket lunar landing vehicles to transport both people and goods from lunar orbit to the lunar bases and return.

Low mass of equipment to be delivered from Earth will be of extreme importance to reducing the transportation tasks, as will early use of indigenous materials to produce simple but heavy items on the moon.

Early use of hydrogen and oxygen obtained from the lunar regolith as rocket propellants will be of great benefit to mining for ^{3}He, by reducing the extent of space launch services. Early use of lunar-produced propellants may be confined to the lunar landing vehicles; later use will extend to cislunar orbit transfer and to planetary exploration. A nuclear thermal rocket departing for Mars from lunar orbit, fueled with lunar hydrogen, may be an attractive means to obtain "fast trip times" to Mars while assuring safety of Earth's biosphere. Thus, a built-in market for the ^{3}He co-products: oxygen and hydrogen, is inherent in any continuing lunar activity.

Crew rotation intervals have a powerful influence upon space transportation mission frequency, as does crew capacity of the flight vehicle transporting them to and from the lunar surface from low lunar orbit. Both of these important factors should improve with time. (see Table II)

A conceptual Lunar Excursion Vehicle (LEV) was defined for this scenario, using hydrogen/oxygen propellants at an oxidizer-to-fuel ratio of 6:1. The specific impulse of its four rocket engines is 465 seconds.

The LEV is reusable with minimal maintenance for five missions. It can carry a four person crew module weighing 3.8 tons (including people), has an inert mass of 6.6 tons; and a usable propellant capacity of 21.4 tons. The lunar landing maneuver requires a velocity change of 2.1 km/sec; ascent requires 1.9 km/sec. The ratio of initial to final mass (mass ratio, or MR) is thus 1.59 from lunar orbit to the surface and 1.52 for an ascent from the surface of the moon to low lunar orbit. The necessity and scope of facilities in lunar orbit is not yet determined. It may prove advantageous to place an automated "propellant depot" there to act as a source of propellants for the flight vehicles. However, widespread lunar surface activities and orbital mechanics may render a single such facility inaccessible for too long. This scenario does not require a permanent lunar orbit facility.

This LEV can place 29.9 tons of payload on the lunar surface, 26.1 tons if a crew module is used, arriving on the moon with empty propellant tanks. Ascent flight with full tanks can place 34.9 tons into lunar orbit; 31.1 if the vehicle is crewed.

A "sortie" mission, flown before lunar-derived propellants are available, uses a portion of this payload capability to deliver to the lunar surface the propellants for ascent flight with a 0.5 ton payload, and can use for descent only the propellant remaining after reserving this ascent propellant plus an allowance for boil-off while on the surface. As 3.7 tons of propellant is required for ascent without crew and 5.6 tons carrying a crew, a maximum of 17.8 and 15.8 tons of propellant, respectively, is available for descent. Payload capability in this mission mode is 20.1 tons and 10.9 tons, respectively. An "inverse sortie" mission originating on the lunar surface, using lunar-produced propellants exclusively, with 13.9 and 7.4 tons descent payload capability, respectively, is used immediately upon the production of adequate lunar O_2 and H_2 and for most of the scenario.

The flight rates to support the scenario assume a "load factor" of 80% to recognize less-than-perfect manifesting of payloads, boiloff of propellant, and the necessity of using flight support equipment to deliver payloads. All payload capabilities used in the scenario are reduced by 20% from nominal values.

As flight frequency is expected to increase to high levels during the mid portion of the equipment placement interval, and crew rotation will constitute a large transportation workload as population on the moon increases, a Block II LEV is introduced in 2025: a four times scale-up of the earlier vehicle, capable of carrying up to 16 persons and four times the deliverable payload of its predecessor. No technological improvements for this Block II LEV are assumed other than extension of vehicle life from 5 to 25 missions.

A cost indicator for any space scenario is the mass which must be placed into low Earth orbit from Earth (MLEO). To derive this factor, the nature of the cislunar transport and lunar landing vehicles must be known, along with the time history of mass and people to be transported. This scenario derives only payload to lunar orbit as a surrogate for MLEO, deferring to future work the characterization of the Lunar Transfer Vehicles (LTVs) and derivation of MLEO.

Lunar Base Human Support Facilities

The first U.S. space station, *Skylab* had a specific mass of 12 tons per person[12]. Space Station *Freedom* will have a larger mass per person. The NASA 90 day study defined a mature lunar base with a staff of 12 which had a mass of over 150 tons, including the electrical power supply and surface transport vehicles.[13] This is 13 tons of base camp per person.

Considering just the inflatable habitat for the Lunar Base[2], the fully equipped living/working quarters for 12 persons will have a mass of almost 50 tons, or about 4 tons per person.

Sviatoslavsky[7] estimates base camp equipment as 258 tons/ton ^3He, with no indication of the number of persons required. Assuming the manning levels established above, 186 persons per ton per year of ^3He, this represents 1.4 tons of base camp per person.

A value of 4 tons of fixed surface support facilities per person is used for this scenario.

In addition to fixed facilities and equipment (a one time investment with maintenance), NASA has estimated recurring needs for supply of food and other consumables, including personal items and mail, to a lunar community[5]. With assumptions for this scenario on the extent of EVA, etc. these NASA rates reduce to a gross amount of 5.4 tons per person year, 18% O_2, 61% H_2O, 16% N_2, 4% food, and 1% personal items.[6]

Hydrogen, oxygen, and nitrogen will be obtained capturing all of the volatiles evolved from the regolith in producing ^3He. All but food and personal effects (clothing, books, cassettes, toiletries, mail, etc.) are locally available. within five years. A sufficient quantity of the consumables O_2, H_2O, and N_2 are thus locally available. **Re-supply from Earth for the human staff is then reduced to about 0.3 tons per person year**, or 17 tons/year per standard mine. A qualifier to this assessment is that nitrogen derived from the regolith will be insufficient to support the early years of the scenario.

Helium 3 Gathering Systems Scenario

A spreadsheet simulation program was formulated to do the bookkeeping for a 60 year scenario. Key output parameters include the time history of total mass which must be provided from Earth to low lunar orbit and the number of people present in space.

Summary plots of relevant data produced by this simulation are presented in Figures 1 through 6.

Table III characterizes the total quantities involved in the scenario. Total ^3He delivered to Earth during the build up interval is 220 tons, with an additional 300 tons delivered during the subsequent 20 years of steady state operation. An accumulated lunar equipment inventory of 130,000 tons is established by 2050, with peak delivery rate from Earth of 6,000 tons per year during the interval 2032-2043.

Lunar industry employment is 2800 persons by 2050. Aggregate manpower in space invested in the 60 year endeavor is 97,000 man-years.

To equip and maintain these industrial complexes, a total of 170,000 tons of cargo, including propellants and gases, are delivered from Earth to LLO. Mining activities permit self-sufficiency in oxygen and hydrogen by the fifth year (2015). Local manufacture from native materials begins in 2025. This manufacturing base achieves 90% self-sufficiency in 2050, delivering an aggregate of 80,000 tons of lunar-manufactured equipment and spares. During the operational interval beyond 2050, the lunar bases provide 11,000 tons/year of LEV propellants, 14,000 tons/year of gases for human support, and 2,300 tons/year of manufactured goods. In addition, marketable commodities are produced as follows:

a. hydrogen - 100,000 tons/year
b. oxygen - 800,000 tons/year
c. nitrogen - 5,300 tons/year
d. helium - 45,000 tons/year
e. free iron - 1 million tons/year
f. hot regolith - 500 million tons/year (candidate for post-processing)

Space transportation includes 6,400 LEV flights, 4,200 for crew rotation and 2,200 to deliver cargo. The peak LEV flight rate is 200 flights in 2024, with an operational era steady state rate of 112 flights per year.

The scale-up of the LEV to reduce the number of crew rotation flights was, in retrospect, not done appropriately. The scenario results indicate that less cargo and a larger passenger capacity is preferable. Future analyses should better define the Block II LEV with benefits of economy of scale, a more suitable mix of payload capacity and passenger capacity and perhaps be used from the beginning of the scenario rather than using the smaller LEV of pre-cursor lunar activities.

As full descent cargo capacity of the crew rotation flights is not required for flights during much of this scenario, almost 50,000 tons of discretionary cargo may be delivered from lunar orbit to the moon during crew rotation missions to further expand activities on the moon. Alternatively, lunar-produced commodities may be delivered to low lunar orbit (LLO) to support resupply of lunar transfer vehicles (LTVs), Mars missions, or other space activities. Future analyses should quantify utilization of this surplus space transportation capacity or reduce the number of flights of a re-designed LEV.

The magnitude of this scenario is large, as are its probable benefits and costs. The principal lesson learned from this simulation is that, if ^3He is to be returned to Earth to supply even a small fraction of our electrical power needs, a major, multi-location lunar community will emerge, populated by several thousand people who will each stay on the moon for at least two years. Vast resources from the moon will be produced for use by other ventures in space, including missions to Mars.

Conclusions

1. A scenario was produced for providing the United States with 200 GW_e average power from fusion reactors on Earth fueled by ^3He, an isotope of helium found in abundance on the surface of the moon.

2. 15 tons per year of this commodity is delivered, which requires the establishment of 50 multi-function facilities on the surface of the moon, each operated by 56 persons resulting in a work force of 2800 persons on the moon by 2050.

3. Each of these facilities is equipped to mine 20 million tons and thermally process 10 million tons per year of regolith to acquire volatile gases, including 300 kg per mine per year of ^3He fusion fuel; to support and transport the human staff; and provide community utilities, including 30 MW_e of electricity. Waste heat from the power supply is used in materials processing on the moon. An estimate of equipment mass at each of these facilities is 680 tons of mining equipment; 890 tons to process the regolith for gases; 123 tons for the nuclear electric power supply; 310 tons to produce supplemental oxygen, iron, and finished products from the hot regolith; and 224 tons to provide housing, life support, and transportation; for a total of approximately 2,200 tons per site.

4. A lunar manufacturing area produces 42 tons per year of spare parts and equipment for each site. With this capability, each site may be supported by 2 flights per year of a Lunar Excursion Vehicle (LEV) capable of carrying 16 passengers.

5. The principal space transportation tasks are crew rotation and initial equipment delivery. Use of native materials to locally produce heavy items for the lunar operation may be possible and advantageous. With capture and use of water, oxygen, and nitrogen from lunar regolith, supply of food and personal items to support the large lunar population appears to be a small task compared to personnel transportation at the beginning and end of tours of duty. Careful derivation of the staffing needs of the industrial sites on the moon appears to be a high priority task of the work ahead.

6. The mass which must be delivered to low lunar orbit for delivery to the lunar bases totals 130,000 tons; 250 tons of mass delivered to lunar orbit for each ton of fusion fuel returned to Earth. This mass constitutes a permanent investment which will permit continued deliveries of fuel well beyond the 20 years of the steady state part of this scenario.

7. Present NASA plans to establish a permanent lunar base may render this scenario both possible and, provided nuclear fusion research confirms desirability of the helium fuel cycle, a socially attractive venture.

8. Future research will alter the value of input data and assumptions from those used here. These alterations may result in an activity several times as attractive as the one displayed by this simulation.

9. The principal utility of this scenario may a stimulus to thinking on the high-leverage elements of the problem and lessen attention to those elements which are less influential to the outcome. For example, the mass of the process pressure vessels to release volatile gases is very important; on-site production of food, although highly desirable to the palate, is not highly influential on the outcome of the scenario.

It is hoped that this scenario will be the genesis of many thoughtful objections to the assumptions and the definition of alternatives as to how we should go about establishing a fully integrated lunar industrial complex, but that it will be persuasive that we should do so.

Acknowledgements

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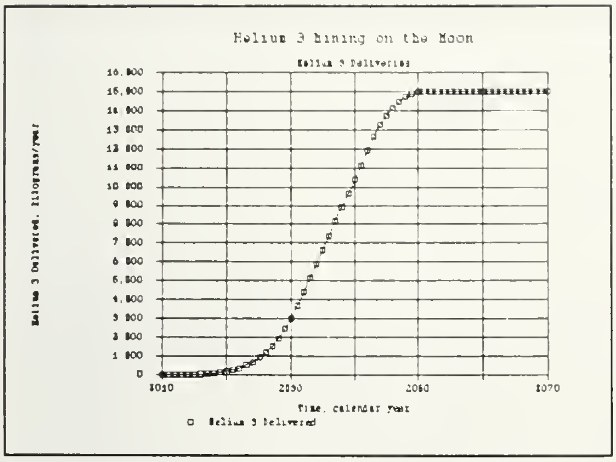


Figure 1

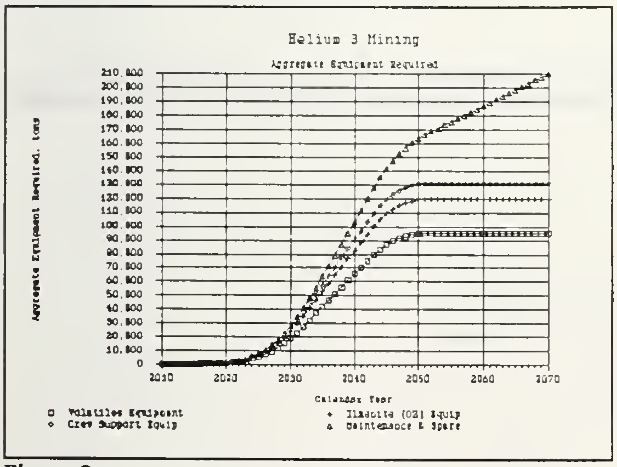
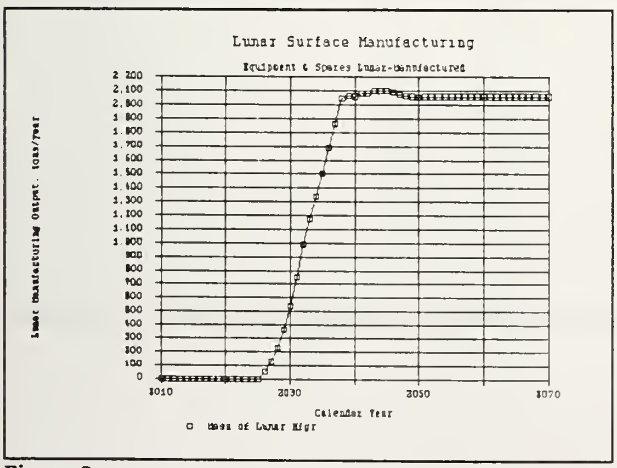


Figure 2



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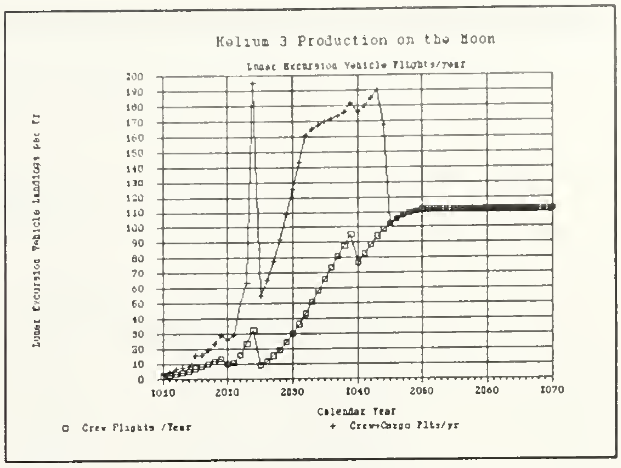

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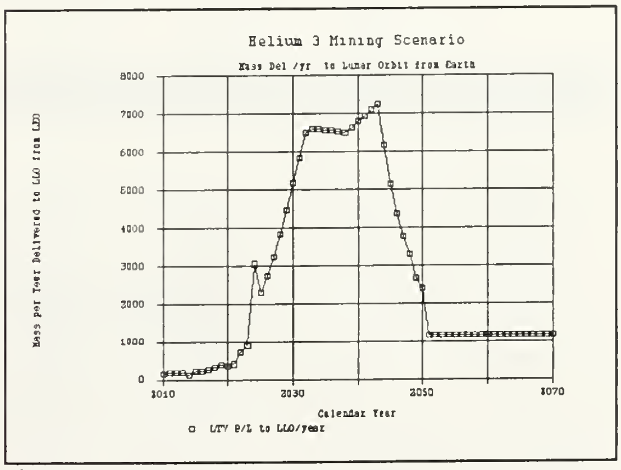

Figure 5

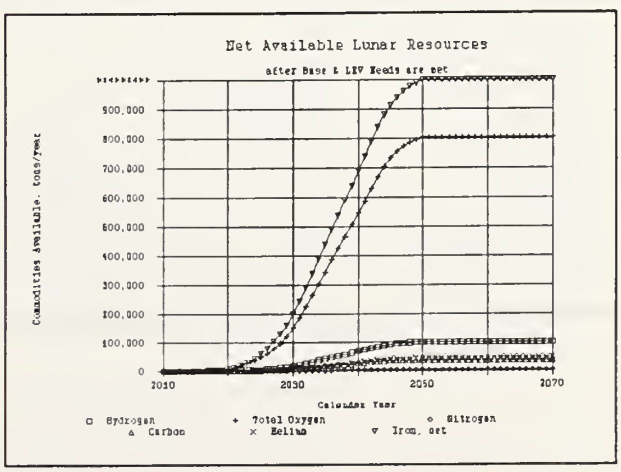

Figure 6

Table I
Integrated Lunar Plant

Byproducts of He-3 Production, tons/ton He-3			
Hydrogen		6100	tons/ton from volatiles
Nitrogen		500	tons/ton from volatiles
Carbon Compounds		5200	tons/ton from volatiles
Water		3300	tons/ton from volatiles
Helium 4		2600	tons/ton from volatiles
Oxygen from Ilmenite		45,867	tons/ton @ O/F = 8.0
Hot Regolith		3.33E+07	tons/ton for post-processing
Iron	@0.05%	16,667	tons/ton magnetically extracted

Table II
Logistics Support of Lunar Mining
Lunar Landing Vehicles Evolution

		Calendar Year					
		2010	2020	2025	2040	2050	2060
Staff, Persons per Mine:		4 to 56	56	56	56	56	56
LEV average persons/flight:		3.1	3.1	12.5	12.5	12.5	12.5
LEV Propellants per Flight:		24.6	24.6	98.5	98.5	98.5	98.5
Average Tour of Duty, months:		10	15	18	24	24	24
Descent Cargo/flight w/crew		8.6	5.8	23.1	23.1	23.1	23.1
Descent Cargo/flt. w/o crew		15.7	10.9	43.5	43.5	43.5	43.5
Crew Use,tons/yr	O2/person	3.67	3.67	3.67	3.67	3.67	3.67
(partial life	H2/person	0.34	0.34	0.34	0.34	0.34	0.34
support system	N2/person	0.80	0.80	0.80	0.80	0.80	0.80
closure)	Dry Food	0.18	0.18	0.18	0.18	0.18	0.18
Personal		0.11	0.11	0.11	0.11	0.11	0.11
Crew Imports tons/yr/person (with use of lunar resources)		0.29	0.29	0.29	0.29	0.29	0.29

Table III
HELIUM-3 SCENARIO SUMMARY

	Placement Phase 2010-2050	Operational Phase 2051-2070	Total Scenario (60 yrs)	
Total He-3 Delivered to Earth, tons:	219	301	520	
GWe-years of Energy Delivered:	2,923	4,007	6,930	
kWe-hours Delivered:	2.6E+13	3.5E+13	6.1E+13	
Number of Mine/Process Locations:	0 to 50	50	50	
Regolith Moved, MM tons total:	14,617	20,034	34,651	
Staffing (sum mye, people on the moon):	38,261	58,900	97,161	
Equipment delivered to the moon, mt:	126,855	6,109	132,964	
Equipment manufactured on the moon:	36,050	43,847	79,897	
Number of LEV Crew Rotation Flights:	1,837	2,348	4,185	
Number of LEV Cargo Flights:	2,165	0	2,165	
Total number of LEV flights:	4,003	2,348	6,351	
Discretionary LEV cargo to the moon:	0	48,630	48,360	
Mass delivered to low lunar orbit: (not including discretionary cargo)	142,966	25,856	168,822	
Accumulated inventory of commodities:				Percent
Hydrogen:	1.3E+06	2.1E+06	3.5E+06	5.0%
Oxygen, or if used with hydrogen to	1.1E+07	1.7E+07	2.8E+07	40.2%
form Water (incl. all H_2 & O_2)	1.2E+07	1.9E+07	3.1E+07	45.2%
Nitrogen:	7.1E+04	1.1E+05	1.8E+05	0.3%
Carbon:	5.1E+05	7.8E+05	1.3E+06	1.9%
Helium:	6.3E+05	9.8E+05	1.6E+06	2.3%
Free Iron (magnetic extraction):	1.4E+07	2.1E+07	3.5E+07	50.3%
Total:	2.7E+07	4.2E+07	6.9E+07	100%

A3.4 Construction materials for an SPS constellation in highly eccentric Earth orbit

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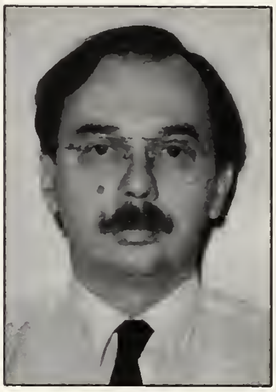

ABSTRACT

Studies of the system architectures for acquisition, processing, and transportation of key non-terrestrial materials (structural metals, propellants, and radiation shielding) to near-Earth space suggest that the ideal target orbit for retrieval of materials from the Moon, nearby asteroids, and the Martian moons is highly eccentric Earth orbit (HEEO) of almost any inclination. Such an orbit would be an excellent site for construction of an SPS constellation. I present a series of scenarios utilizing several modes of propulsion and including both propulsive and aerobraking modes of capture into the target orbit. Very high mass-payback ratios (MPBRs) are possible in several of these scenarios.

RESUME

Les études d'architecture de systèmes pour l'extraction, le traitement et le transport à proximité de la Terre de matériaux non-terrestres (métaux de structure, propergols, et boucliers antiradiation) suggèrent que la meilleure orbite pour récupérer les matériaux de la Lune, des astéroïdes proches et des lunes martiennes est une orbite terrestre très allongée. Cette orbite serait un excellent emplacement pour la construction d'un ensemble de SPS.

SPS Raw-Materials Sources

Construction of a Solar Power Satellite (SPS) system, which in general contains high-technology components lifted from Earth and relatively low-technology components made in space, is made less expensive by choosing orbits for the system so as to minimize transportation costs both from Earth and from the site of extraterrestrial resource extraction. The SPS site must also permit easy return to Earth and to the resource location. A similar system architecture problem is that of determining the optimum location for transportation nodes for advanced human exploration of the Solar System. This problem has been studied in detail by Clark (1990), who finds that highly eccentric planetary orbits offer a number of advantages over low planetary orbits or synchronous orbits. We expand that investigation to include the case where large masses of non-terrestrial material are required by the system for radiation shielding, metallic structures, propellants, or life support. Because of the traditional assumption that SPS systems will be constructed in geosynchronous orbit (GEO), we will use GEO as the basis of comparison. The mission architectures studied are defined in Table 1.

Delta V Requirements for Launch from Earth

We consider launch from Earth in three steps: launch site to LEO; transfer orbit from LEO to the SPS orbit; and velocity-matching at the SPS orbit. For a typical launch site, the delta V requirement for the first step is about 8,500 m/s. The delta V for the second step, injection into geosynchronous transfer orbit (GTO), requires 2491 m/s, and circularization in GEO requires another 1461 m/s, for a total of 12452 m/s from Earth to GEO. By comparison, injection from LEO into a transfer orbit reaching from 300 km out to the Moon requires 3113 m/s. To lift the perigee to an altitude of 6000 km, out of the Van Allen radiation belts, requires an apogee burn of only 63 m/s, for a total of 11676 m/s from Earth to HEEO. Thus HEEO is more accessible to Earth than GEO. The Molniya-type orbit, a mild type of HEEO widely used by Soviet communications satellites, is essentially an inclined GTO with a total delta V cost of 11050 m/s from Earth.

Electromagnetic (EM) launch from Earth into LEO is very inefficient, since the low launch elevation angles needed to reach LEO efficiently are ruled out by excessive atmospheric heating and deceleration of the projectile. Also, of course, EM launch is limited to small payloads (probably a few kg to a few hundred kg) that are

Table 1
Mission Architectures Studied

Earth launch:
E1. Direct rocket launch from Earth
E2. Electromagnetic (EM) launch from Earth

Moon resource retrieval:
M1. Retrieval of lunar materials; all delta Vs are propulsive, using Earth propellants,
M2. Retrieval of lunar materials; aerobraking is used where possible, and only Earth propellants are used for the other delta Vs,
M3. All delta Vs are propulsive, with lunar-derived liquid oxygen (LLOX) used for all burns above LEO,
M4. Aerobraking is used where possible, with LLOX used for all burns above LEO,
M5. Aerobrakes made from lunar material are used where possible; LLOX used for all burns above LEO,
M6. Electromagnetic (EM) launch is used to get LLOX off the Moon; all later delta Vs are propulsive,
M7. EM launch and lunar-derived aerobrakes are used, with other delta Vs utilizing LLOX.

Near-Earth Asteroid resource retrieval:
A1. Retrieval of NEA materials; all delta Vs are propulsive, using Earth propellants,
A2. Retrieval of NEA materials; aerobraking is used where possible, and only Earth propellants are used for the other delta Vs,
A3. All delta Vs are propulsive, with NEA-derived liquid water used for all delta Vs above LEO,
A4. Aerobraking is used where possible, with water used for all delta Vs above LEO,
A5. Aerobrakes made from NEA material are used where possible; water used for delta Vs above LEO,
A6. Electromagnetic (EM) launch is used to get water off the NEA; all later delta Vs are propulsive,
A7. EM launch and NEA-derived aerobrakes are used, with water used for all other delta Vs

rugged enough to withstand accelerations of thousands of gravities. Raising the launch elevation angle high enough to mitigate the heating and drag problems causes the projectile to reach apogee with a velocity far less than local circular orbit velocity. Then a rocket burn of about 3000 m/s is required to insert the payload into orbit. But this rocket engine needs to be robust enough to survive the launch acceleration load! Assuming electromagnetic launch of materials such as propellants and structural members can be accomplished, it is interesting to note that EM launch directly to very high altitudes is relatively easy. EM launch into a trajectory that reaches apogee at GEO can insert a payload into GTO with an apogee rocket engine burn that delivers only about 200 m/s, or directly into GEO with a burn of 1600 m/s. Even more remote orbits, especially those of high eccentricity, are even easier to reach via EM launch. The type example of highly eccentric Earth orbits used herein, with a perigee of 6000 km and an apogee of 400,000 km, can be reached with an apogee burn that delivers about 150 m/s. The problem with this model is that a fixed EM launcher, with kilometer dimensions, has only a brief opportunity to shoot into a given HEEO once a day. The (very expensive) launcher would be extremely poorly utilized if it serviced only a single HEEO.

The delta V calculations for Earth launch are summarized in Table 2.

Delta V Requirements for Launch from the Moon

Any attempt to export materials from the Moon must first install mining, processing, and launch facilities on the Moon. The propulsive delta V requirement for the outbound leg from Earth to the surface of the Moon is 14525 m/s. Of this, 8500 m/s must be terrestrial propellant expended during ascent to LEO. The remaining 6025 m/s can utilize lunar liquid oxygen to reduce the amount of propellant that must be lifted from Earth.

Takeoff from the Moon to low lunar orbit (LLO) requires a delta V of 1680 m/s, and departure through the inner Lagrange point requires another 420 m/s. From there, 812 m/s must be removed from the vehicle's orbital velocity to permit it to drop down to a perigee altitude of 300 km. A velocity reduction of 3113 m/s is required at perigee to enter LEO. The total delta V from the lunar surface to LEO is then 6025 m/s. If aerobraking is employed, then the first two engine burns are the same and the third burn is 815 m/s, sufficient to drop the perigee into the upper atmosphere for an aerobraking pass. After aerobraking to an orbit with an apogee of 300 km, a small apogee burn of 57 m/s is needed to lift the perigee out of the atmosphere and circularize in LEO. The total propulsive delta V for aerobraking return from the lunar surface to LEO is then 2972 m/s. This improvement is of course offset by the penalty incurred by having to lift the aerobrake from the Moon, and, with all except the most generous technological assumptions, to carry it from Earth to the Moon. The aerobrake required for this mission will have a mass of about 10% of the payload mass. If electromagnetic launch is used to get from the lunar surface to a return trajectory with perigee at LEO, then a delta V of 2491 m/s is needed at perigee to enter LEO. If electromagnetic launch could be combined with aerobraking (a feat that seems geometrically impossible), the total propulsive delta V requirement would then be only the 60 m/s needed to circularize in LEO after braking.

The seven variants of lunar return missions that are considered in this paper are defined in Table 1. Lunar-derived propellant is limited to liquid oxygen for use in hydrogen-oxygen chemical rocket motors. Fabrication of aerobrakes from lunar materials is also considered in certain of the cases.

The propulsive delta V calculations for these options are summarized and compared to the case of direct ascent from Earth for three types of target orbits, LEO, GEO, and HEEO in Table 2. Several generalizations are in order, the first two of which are well-known. First, launch from the Moon to any of these orbits involves a much smaller delta V than any form of rocket launch from Earth. Second, the use of aerobraking promises a major

reduction in propulsive delta V requirements. Third, EM launch from the Moon without aerobraking is not a reasonable way to get to LEO, given the small propulsive delta V advantage bought by spending vast sums on a lunar EM launch facility. Lunar EM launch to GEO may be more competive, but still requires nearly 1000 m/s post-launch propulsive delta V. But lunar EM launch to HEEO is extremely attractive. When aerobraking is combined with lunar EM launch, LEO becomes extremely accessible, but access to GEO and HEEO is not improved. This option seems the least plausible from the perspective of technology development, and fails to improve on the best options available without it. Fourth, from the Moon, HEEO is in every case more readily reached than GEO. We found the same result for launch from Earth.

Delta V Requirements for Launch from NEAs

Since over 150 near-Earth asteroids (NEAs) are known, it is necessary to define a "typical" mission scenario for return of asteroidal materials. We assume a delta V of 4000 m/s for transfer from LEO to interception of the asteroid, and 1000 m/s for orbit-matching upon arrival, for a total outbound delta V of 5000 m/s. In fact, the lowest possible outbound delta V is about 3200 m/s, and 16 NEAs are known to have outbound delta Vs under 6150 m/s, out of 104 for which the calculations have been done. The best cases known are 1989 ML (delta V out = 4250 m/s) and 1982 DB (4453 m/s).

For return to Earth, we allow 10 m/s for escape from the asteroid (the escape velocity of a 6 km diameter asteroid is 5 m/s) and 500 m/s for injection into an orbit that intercepts Earth. Return delta Vs have been calculated for few asteroids: 3361 Orpheus, 260 m/s; 1943 Anteros, 390 m/s; 1982 DB, 60 m/s; 1982 XB, 220 m/s; 1980 AA, 360 m/s. We then assume a V(infinity) of 6000 m/s for the returning spacecraft as it approaches Earth. The delta V requirement is then 4800 m/s to enter LEO, 3729 m/s to enter GEO, and 1690 m/s to enter HEEO. If aerobraking is used, the propulsive delta V requirements are then 60 m/s into LEO, 996 m/s into GEO, and 60 m/s into HEEO (for the apogee burn after aerobraking).

The seven variants of asteroid return missions that are considered are also described in Table 1. Asteroid-derived propellant is limited to liquid water for use in solar thermal or nuclear thermal rocket motors. The only other transportation-system use of asteroidal materials is, as in the lunar cases given above, in aerobrakes fabricated on the asteroid.

The delta Vs calculated for these seven cases are presented in Table 2. The general conclusions from this exercise are: first, for any given set of technological assumptions, HEEO is always much more accessible than GEO. Second, any orbit with a perigee close to the top of the atmosphere is very readily accessible. Third, aerobraking is even more advantageous for asteroid resource return missions than for lunar return missions: the propulsive delta Vs for return to LEO or HEEO from NEAs are 5

Table 2
Delta Vs for the Sixteen Basic Mission Architectures
delta V (m/s)

Event		E1	E2	M1,3	M2,4,5	M6	M7	A1,3	A2,4,5	A6	A7
E to LEO		8500	3000	8500	8500	8500	8500	8500	8500	8500	8500
LEO to GTO		2491									
GTO to GEO		1461	1600								
LEO to TO		3113									
TO to HEEO		63	150								
LEO to intercept				3113	3113	3113	3113	4000	4000	4000	4000
orbit match				812	812	812	812	1000	1000	1000	1000
landing				2100	2100	2100	2100	10	10	10	10
takeoff				2100	2100			10	10		
to E intercept								500	500		
capture	LEO			3925	872	2491	60	4800	60	4800	60
+trim to:	GEO			1538	1538	996	996	3729	1480	3729	1480
	HEEO			750	750	60	60	1690	63	1690	63
Sum to LEO		8500	3000	6025	2972	2491	60	5310	570	4800	60
Sum to GEO		12452	1600	3638	3638	996	996	4239	1990	3729	1480
Sum to HEEO		11676	150	2850	2850	60	60	2200	573	1690	63
		E1	E2	M1,3	M2,4,5	M6	M7	A1,3	A2,4,5	A6	A7

times smaller than for similar missions from the Moon (570 vs. 2900 m/s). For missions without EM launch, return of asteroidal material via aerobraking has by far the smallest delta V. If EM launch is assumed, direct launch from the Moon and aerobraked return from asteroids both give extraordinarily low propulsive delta V requirements of about 60 m/s, about equal to the best known asteroidal return opportunity without EM launch (1982 DB).

Mass Payback Ratios to LEO

The Mass Payback Ratio is the total mass of useful material delivered to the target orbit per ton of mass that had to be injected into LEO to carry out the retrieval. For the various mission architectures defined in Table 1, using the delta Vs calculated in Table 2, we can calculate the MPBRs for the delivery of useful materials to LEO, GEO, and HEEO. These MPBRs are presented in Table 3. By definition, the MPBRs for direct delivery of terrestrial material to LEO are 1.000. The MPBR for Earth launch to GEO using hydrogen-oxygen chemical propulsion with a specific impulse of 420 seconds is 0.384, and to HEEO, 0.472.

For H/O propulsion, transfer from LEO to GEO (our scenario E1) gives a payload ratio of 0.380. Direct ascent to the Moon can land a payload of 0.230. Liftoff from the Moon and all-propulsive return to LEO (scenario M1) yields a mass payback ratio of 0.036. If an aerobrake with a mass of 10% of the payload mass is used (scenario M2), the overall mass payback is 0.118. With launch costs to LEO running close to $10,000 per kilogram, only lunar commodities with values (in LEO) of at least $90,000/kg would be worth retrieving even if energy were the only cost consideration.

Using the same technology base, a direct retrieval mission to a NEA (scenario A1) could deliver a mass of 0.301 to its surface, better than could be delivered to the lunar surface. All-propulsive return to LEO is, however, rather costly (5310 m/s): the MPBR is 0.068, little better than for return from the Moon, and still less than unity.

Adding the ability to aerobrake during return to LEO has a very positive effect on the MPBR. The total propulsive delta V for return is then only 573 m/s, and the MPBR is 0.615. For the best known asteroid mission, the MPBR is about 6.

The next level of technological complexity is to carry out extraction of propellant from the surface of the body for use in the return to Earth. For the Moon, we assume extraction of liquid oxygen and its subsequent use in a hydrogen-oxygen engine in combination with terrestrial liquid hydrogen (scenario M3). For the asteroids, we assume extraction of water, which is then used as the work-

Table 3
Mass Payback Ratios
(single mission)

Mission	Return to LEO	Return to GEO	Return to HEEO
E1	1.000	0.334	0.418
E2*	1.000	1.684	2.782
M1	0.036	0.063	0.145
M2	0.118**	-	-
M3	0.202	0.502	0.707
M4	0.505**	-	-
M5	0.715**	-	-
M6	1.020	0.532	3.89
M7	55.	-	-
A1	0.068	0.134	0.292
A2	0.615	0.226***	0.804****
A3	1.672	2.710	5.65
A4	1.431	0.978***	1.86****
A5	8.50	5.40***	8.48****
A6	0.090	0.60	0.325
A7	0.800	0.918	1.605

* The numbers reported for scenario M2 are the mass delivered to the destination orbit relative to the amount than can be delivered to LEO, assuming a fixed projectile mass.

** Assuming an aerobrake mass fraction of 0.1 (low energy dissipation)

*** Assuming an aerobrake mass fraction of 0.3 (high energy dissipation)

**** Assuming an aerobrake mass fraction of 0.2 (moderate energy dissipation)

ing fluid in a solar thermal "steam rocket" (scenario A3). The energy source is a 1-ton inflatable solar collector delivering 52 MW thermal power at 1 AU. The thrust chamber expels steam witha specific impulse of 220 s. The single-mission MPBR using lunar liquid oxygen (LLOX) is 0.202, and the comparable asteroidal number is 1.672. These scenarios assume no aerobraking.

The next scenario, in which aerobraking is used along with locally-derived propellant for the return to LEO, gives an MPBR of 0.505 (scenario M4) for the Moon and 1.431 (A4) for the asteroids.

Next in order of complexity and difficulty would be the use of local materials to make both propellant and crude aerobrakes. This raises the lunar single-mission MPBR to 0.715 (M5), and the asteroids reach 8.50 (A5). In both of these cases the mass of aerobrake material returned to LEO is not counted as delivered resources.

Finally we consider EM launch from the Moon and asteroids, both with (M6, A6) and without (M7, A7) aerobraking. Return from the Moon to LEO via EM launch and aerobraking has a very attractive MPBR of 55, but this combination of technologies seems very improbable. The other combinations are uninteresting.

Mass Payback Ratios to GEO

Direct Earth launch to GEO passes through LEO. The mass delivered to GEO is 0.334 of the LEO payload, assuming hydrogen-oxygen propulsion throughout. EM launch from Earth, followed by a 3000 m/s burn of a circularization stage, is a very inefficient approach to reaching LEO. For GEO, the circularization burn is only about 1600 m/s, so the delivered payload at GEO is a higher fraction of the launch weight of the projectile than it would be if sent to LEO (E2).

Aerobraking is not a useful technique for reaching GEO from the Moon, and the corresponding MPBRs have been omitted from Table 3. Launch from the Moon using LLOX provides an MPBR of 0.502 to GEO. EM launch from the Moon is similarly unattractive to GEO.

Asteroid missions using asteroidal water as the propellant (A3) offer an MPBR of 2.71 to GEO. Carrying along an aerobrake from Earth (A4) actually lowers the MPBR to 0.978, since the latter requires carrying the heavy aerobrake all the way to the asteroid and back, whereas the former picks up on the asteroid the water it needs for propulsive capture at Earth. The best scenario uses both asteroid-derived propellant and an aerobrake made of asteroidal materials (A5): the MPBR for a single mission is 5.40. EM launch from asteroids to GEO looks uninteresting.

Note that the highest MPBRs for return to GEO are for asteroidal missions. These MPBRs are generally similar to or less than those for return of asteroidal material to LEO. The clear exceptions are A1 and A3, which, because of the absence of aerobraking, are very sensitive to the large delta V requirement for capture into LEO.

Mass Payback Ratios to HEEO

Both chemical and EM launch from Earth provide higher masses of material in HEEO than in GEO.

Launch from the Moon to HEEO using LLOX offers an MPBR of 0.707. Again, HEEO is more accessible than GEO from the Moon. Aerobraking confers no advantage on travel from the Moon to HEEO. EM launch from the Moon to HEEO without aerobraking has a good MPBR of 3.89.

Return of asteroidal material to HEEO is in every case more favorable than to GEO. Using asteroidal water as a propellant for an all-propulsive return to HEEO (A3) gives as MPBR of 5.65. Using an aerobrake transported from Earth for capture into HEEO (A4) has an MPBR of 1.86, and combining asteroid-derived propellant with an asteroid-derived aerobrake gives an MPBR of 8.5.

EM launch from an asteroid is not very attractive.

Bootstrapping with Locally-Derived Propellants

With resusable spacecraft, there are great advantages to returning non-terrestrial propellants to LEO or HEEO and then using them for the next outbound mission. As an example, the use of LLOX at a space station in LEO for refuelling lunar spacecraft (combined with aerobraking) provides an MPBR of about 2.5. Lunar base proponents see this as a potentially profitable endeavour. Similarly, use of asteroidal water in a solar thermal rocket (A3), with a single-mission MPBR of 5.65 to HEEO, can also be enhanced by propellant bootstrapping. A 3.8 tonne spacecraft (with a fully fuelled weight of 17.7 t) is lifted into LEO, departs to an asteroid, and delivers 100 t of water back to a platform in HEEO. Then 3.6 t of this water is electrolysed into hydrogen and oxygen using solar power and is used to fuel a chemical rocket to return the spacecraft to an asteroid (only 2200 m/s from HEEO, vs. 5010 m/s from LEO). On the second round trip the vehicle returns 100 t of water (a net gain of 196.4 t). Thus the MPBR after the second flight is 196.4/17.7 = 10.7. Similarly, after three flights the MPBR is 15.7.

Since there is now a supply of water (and hence of hydrogen and oxygen) in HEEO, it is now possible to launch a new 3.8 ton spacecraft from LEO into HEEO to be refueled there. The mass departing LEO is 12 t. Upon receiving 3.6 t of fuel in HEEO, the spacecraft departs to an asteroid and returns with 100 t of water. The MPBR after one flight is 8.5; after two flights, 15.8; and after three flights, 24.

The advantages of bootstrapping become most evident when applied to an already promising single-mission scenario such as A5 to HEEO. There the first mission departs from LEO using terrestrial propellant. Subsequent missions are not only fueled with asteroidally derived hydrogen and oxygen and protected by an asteroid-derived aerobrake, but also depart from a base that is already traveling nearly at escape velocity. We improve the performance by using an aerobrake made out of asteroidal material. In this scenario the MPBRs are

8.4 (1 flight), 16.7 (2 flights), and 24.9 (3 flights). After a new spacecraft is lifted to HEEO and fuelled with asteroid-derived hydrogen and oxygen, the MPBRs are 13.0 (1 flight), 25.7 (2 flights), and 38.4 (3 flights). **This performance is typical of good asteroidal retrieval missions. The best known cases (1982 DB and 1989 ML) are much better.**

In addition to the water payload, each mission leaves a used 20 t asteroidal aerobrake in HEEO for processing. Only a small fraction of the water is consumed in running the next retrieval mission to an asteroid. Counting this material as a resource, the MPBR after 3 flights (scenario A5) is 30. The new spacecraft, fuelled only in HEEO, will show an MPBR of 46. The remaining water (296 t after 3 flights) is available to support SEI-type activities in the manner described by Clark (1990) for an HEEO staging base. The time required to build up a large inventory can be as short as six years by using all the propellant returned from the first 3-year mission to dispatch an armada of new spacecraft from HEEO. Since the fuel use from HEEO to the asteroid is only 1.8 t per mission, over 50 spacecraft could be fueled by the first 100 t of water returned. They would bring back 5000 t of water three years later.

Clearly, asteroid return missions of this type can return metals, silicates, or other volatiles in addition to water, with MPBRs much larger than 10. The return of NEA material to HEEO is therefore a very attractive source of construction and transportation materials for an SPS system. Using a comparable level of technology, such large MPBRs are not available from any other source or at any other location.

Conclusions

HEEO (in our reference example, 6000 to 400000 km altitude) has several considerable advantages relative to GEO as a site for construction of SPS constellations:

1) It is more accessible than GEO via chemical launch from Earth,

2) It is much more accessible than GEO via electromagnetic launch from Earth,

3) It is more accessible than GEO for launch from the Moon,

4) It is more accessible than GEO for launch from near-Earth asteroids.

5) From HEEO there is much easier access to Earth than from GEO (a delta V of under 100 m/s vs. 1461 m/s for return to atmospheric entry), easier access to the Moon than from GEO (2900 vs. 3500 m/s), and easier access to the typical NEA than from GEO (3000 vs. 5400 m/s).

6) The radiation hazard in HEEO is no worse than in GEO, and the cost of providing shielding from any source will always be less in HEEO.

7) The high MPBRs available for return of asteroidal material suggest a careful look at a variety of schemes for return of asteroidal material to HEEO.

References

B. C. Clark, Benefits of HEPO as Staging Locations for Human Interplanetary Exploration. IAF-90-339 (1990).

A3.5 ^{3}He for Fusion Power: The Willie Sutton principle

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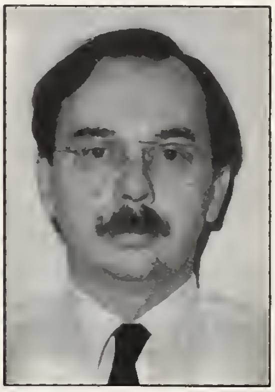

ABSTRACT

Assuming that the technological difficulties associated with D-^{3}He fusion (ignition temperature, neutron-producing side reactions) can be overcome, ^{3}He is likely to become the most valuable commodity in Solar System commerce. It is therefore important to assess the relative costs of acquiring ^{3}He from different sources. I present here a comparison of the energetic cost of acquiring, isolating and transporting ^{3}He to Earth from the two most attractive types of sources available, the lunar regolith and the atmospheres of the Jovian planets. I show that the total energy expended per tonne of ^{3}He retrieved from the atmosphere of Uranus is at least 1000 times less than that required to recover ^{3}He from the lunar regolith.

RESUME

Si les difficultés techniques de la fusion du deutérium avec l'hélium 3 (température de réaction, production de neutrons par réactions parasites) sont surmontées, ^{3}He sera la ressource la plus intéressante du système solaire. On compare les coûts énergétiques d'extraction et de transport à la Terre de ^{3}He en provenance de la régolithe lunaire et des atmosphères d'Uranus et de Neptune. Les coûts sont au moins mille fois moindres dans le cas d'Uranus que dans celui de la Lune.

^{3}He as a Clean Fusion Fuel

Intrinsically, the isotope ^{3}He seems attractive as a fusion reactor fuel, since the reaction ^{3}He + D is extraordinarily "clean", i. e., the reaction

$$^{3}He + D => {}^{4}He + p \qquad (1)$$

has a very low neutron yield and generates 19 GW yr per tonne of ^{3}He consumed.[1] If the problems posed by the Coulomb barrier for reaction (twice as high as for D-T) and by D-D side-reactions can be overcome, this would be a highly desirable energy source. Unfortunately, the isotope ^{3}He is of negligible abundance on Earth because it was extremely inefficiently retained during formation of the terrestrial planets, and because is so light that it readily escapes from Earth's gravitational field. The total terrestrial inventory of ^{3}He, about 20 t, is small compared to the annual power consumption of Earth (8500 GW, or about 450 t of ^{3}He). It has therefore been neglected as a practical fuel. But the market for ^{3}He is so large, and the energy content of ^{3}He so high (\$1.4 to 1.8×10^{10}/t), that it may be economically possible to recover it from other Solar System bodies and return it to Earth for use as a fusion fuel. Accordingly, I shall review the data on the occurrence and accessibility of ^{3}He in the solar system.

^{3}He Occurrence in the Solar System

^{3}He is a direct product of Big Bang nucleosynthesis, produced by reactions of deuterium and by tritium decay in the Big Bang fireball. As such, it is distributed almost evenly throughout the stellar and interstellar matter of the Universe. About 20% of the mass of the universe is helium, of which 200 ppm is ^{3}He. Thus ^{3}He makes up about 40 ppm of the mass of stellar material, including our Sun. The solar wind, the stream of hot, ionized gas emitted by the Sun into the interstellar medium, contains ^{3}He and constantly irradiates the terrestrial planet region with a fast, diffuse stream of it and other solar gases,

mostly hydrogen and helium isotopes. At Earth's orbit the solar wind flux during normal (quiet Sun) conditions is typically $3x10^8$ particles per square centimeter per second, for a ^{3}He flux of about 10^4 ^{3}He ions per cm^2 second. These ions are implanted to very shallow depths in any solid surface that is exposed to the solar wind. Earth itself is shielded from the solar wind flux by its large magnetosphere, but the Moon does not have an intrinsic magnetic field strong enough to stand off the solar wind (i. e., the average magnetic field energy density at the lunar surface, $B^2/8\pi$) is much less than the kinetic energy density of the solar wind, $\rho v^2/2$. Further, the Moon has no atmosphere to stop the solar wind ions before they impact the luar surface. Thus the Moon, like other solid solar system bodies that lack atmospheres and strong magnetic fields, is directly bombarded by solar wind ions.

^{3}He is not only ubiquitous in stars, but also in gas-giant planets. Helium makes up about 22% of the mass of the modern Universe, and about the same fraction of all Sun-like stars. During the formation of the terrestrial planets, free hydrogen and helium were retained very efficiently by gas-giant planets (Jupiter, Saturn, Uranus and Neptune), which formed at very low temperatures far from the Sun. But hydrogen and helium were excluded almost perfectly from rocky bodies such as Earth and the Moon, which formed at much higher temperatures.[2] Helium makes up 19(±3)% of the atmosphere of Jupiter and 13(±4)% of the mass of Saturn's atmosphere, where the slight depletion is believed to be due to the precipitation of helium-rich droplets at very high pressures in Saturn's interior. The best figure for the helium content of the atmosphere of Uranus is 26(±5)%, which, like the figure cited above for Jupiter, is compatible with the solar (i. e., cosmic) hydrogen:helium ratio.[3] A similar figure is likely for Neptune. The solar ^{3}He:^{4}He ratio is about $1.78x10^{-4}$. Hydrogen and helium are "permanent gases" in the Solar System.

Extraction of ^{3}He from the Moon

Recent studies at the University of Wisconsin have made a case that ^{3}He may be sufficiently abundant in the lunar regolith to merit extraction and return to Earth.[4] On the Moon, as on other airless Solar System bodies that are exposed to irradiation by the solar wind, isotopes of hydrogen and helium (and much smaller amounts of other stable elements) are implanted in solid surfaces.

The Moon has a surface area of $4x10^{17}$ cm^2. Assuming that the average depth of useable regolith is 2.5 meters, the Moon contains about 2.5 micrograms of ^{3}He per square centimeter, for a total of 10^{12} grams of ^{3}He for the entire Moon. There is approximately one ton of ^{3}He per 100 million tons of lunar regolith: extracting that one ton of valuable material with a reasonable extraction efficiency of 50% requires heating $2x10^8$ tons of dirt to a temperature of at least 700°C (about 1000K). The extraction energy required is then $2x10^{18}$ ergs per gram of ^{3}He. The energy content of a gram of ^{3}He, when burned with deuterium, is $6x10^{18}$ ergs. Thus the "investment return" on energy expended to extract ^{3}He from the Moon is about 3:1. But the concentration of ^{3}He varies strikingly both horizontally and vertically, in ways very difficult to extrapolate from the information gathered by the Apollo and Luna sample return missions. As a result, unfortunately, the science data base on the abundance and distribution of helium isotopes on the Moon is so scanty that it is not presently possible to estimate the total ^{3}He abundance at all accurately: within the uncertainties (about a factor of three), ^{3}He may be only marginally worthy of extraction, or it may be abundant enough to meet the energy needs of Earth for the next millenium.

Interestingly, the transportation energy requirement for return of material from the surface of the Moon to the Earth, about $1.7x10^{11}$ erg/g, which usually dominates the energetics of lunar sample return missions, is completely negligible compared to the 10-million-times-larger extraction energy cost.

The Jovian Planets

The visible atmosphere of Uranus (above the 6 bar pressure level) contains about one ton of ^{3}He per $3x10^4$ tons of atmosphere, about 3000 times as high a concentration as in the lunar regolith. The atmospheric temperature is 60 K at that level, which is only 31 Kelvins above the saturation temperature of hydrogen. The energy required to separate helium from hydrogen by condensing the hydrogen and helium is about $2.5x10^{14}$ ergs per gram of ^{3}He. The total ^{3}He content of the atmosphere of Uranus above the 6 bar level is $8x10^{18}$ grams, some 8 million times larger than the most probable amount on the Moon. This would be enough to meet the energy needs of 10^{10} people at present North American or Western European consumption rates for $2x10^9$ years. But the visible atmosphere is merely a lower limit on the total abundance of hydrogen and helium isotopes on Uranus. Hubbard and Marley have produced internal models for Uranus that show that about 14% of the planetary mass is free hydrogen and helium.[5] That is equivalent to $1.4x10^{28}$ gm of helium, or $2.5x10^{24}$ gm of ^{3}He, more than 10^{12} times the amount on the Moon, enough for 10^{15} years of global energy consumption.

Using 25500 km as the mean radius of Uranus and $1.0x10^{29}$ grams as the planetary mass, the escape velocity from the equatorial region is $2.2x10^6$ cm/sec. The rotational velocity of Uranus at the equator is $3x10^5$ cm/sec, so the propulsive ΔV requirement is $1.9x10^6$ cm/s to reach escape.

The velocity that the departing payload must have relative to Uranus in order to intersect Earth's orbit ($V_{\infty,U>E}$) is

$$V_{\infty,U>E} = V_{circ,U} - V_{transfer,U>E} = [GM_{sun}/r]^{\frac{1}{2}} - [GM_{sun}(2/r-1/a)]^{\frac{1}{2}} \qquad (2)$$

where a is the semimajor axis of the Uranus-to-Earth Hohmann transfer orbit and r is the distance of Uranus from the Sun at the time of departure. Converting r (cm) to R (AU) and a (cm) to A (AU) gives

$$V_{\infty,U>E} = 30(1/A - 1/R)^{\frac{1}{2}} \text{ km/s} = 30(1/10.1 - 1/19.2)^{\frac{1}{2}} = 6.51 \text{ km/s} \qquad (3)$$

This calculation neglects Saturn and Jupiter swingbys, ei-

ther of which could dramatically lower the injection delta V required for return from Uranus to Earth.

The injection velocity required to supply enough energy to reach escape velocity and enter an Earth-intersecting heliocentric orbit is

$$V_{inj} = (V_{esc}^2 + V_{\infty,U>E}^2)^{\frac{1}{2}} = (19.0^2 + 6.5^2)^{\frac{1}{2}} = 20.1 \text{ km/s} \qquad (4)$$

The mass ratio of a vehicle designed to transport ^3He from Uranus to Earth can be calculated from the rocket equation. Let us assume a single-stage nuclear rocket using liquid hydrogen as the working fluid, operating with a specific impulse of 1200 sec. The mass ratio is then $\exp(-\Delta V/gI_{sp}) = \exp(-1.7) = 0.175$. Thus 4.7 tons of liquid hydrogen is required to lift each ton of payload to escape velocity from Uranus and inject it into an Earth-intersecting trajectory. The propulsive energy requirement amounts to $2\text{x}10^{12}$ erg/g of ^3He.

It is certainly interesting that the propulsive energy requirement for return to Earth from Uranus is only about $(20/6)^2 = 11$ times as large as from the Moon. But in the case of the Moon we saw that extraction energy costs were some 10^7 times larger than the propulsive energy costs. We therefore must sketch out a method of deriving liquid ^3He from the Uranus atmosphere and estimate the extraction energy costs for separating it from the hydrogen and methane with which it mixed. The purpose of this exercise is only to illustrate one plausible scheme for ^3He return and to estimate the mass and energy requirements for the processing equipment and energy source as a feasibility demonstration. No attempt is made to settle upon the best means of carrying out these processes or to optimize any part of the system.

Extraction and Separation Systems

As an illustrative point design, I consider a hot-air balloon floating in the atmosphere of Uranus near the tropopause, at the level where the pressure is 6 bars and the temperature is 60 K. The atmosphere at the tropopause is quite clear and stable. Methane, with a mole fraction of 0.02, is close to saturation. Helium has a mole fraction of 0.26, and hydrogen, 0.72. The mean molecular weight is 2.6. The density of the atmosphere at this level is 2.7 times that at the surface of Earth. The acceleration of gravity is 1.0 Earth gravities.

The scale of the mission is set by requiring the return of 10 tonnes of liquid ^3He after a processing period of one Earth year.

The power supply for the mission is a nuclear reactor capable of delivering 10 MW thermal power. The reactor weight is taken to be 5 tonnes. The reactor is used for processing the Uranus atmosphere, making liquid hydrogen and helium, and separating the helium isotopes. Upon completion of the processing, the reactor is used as a nuclear thermal rocket, with Uranus-derived liquid hydrogen as the working fluid, to escape Uranus as return on an Earth-intersecting trajectory. The mass budget for the return vehicle (Table 1) also includes 3 t for the engine nozzle and pumps, 2 t for refrigeration equipment, 5 t of structures and integral tankage, 117 t of liquid hydrogen propellant, and 8 t allowance for extra propellant (5 t) and disposable tankage (3t). The total takeoff mass from Uranus is 150 t.

Upon arrival at Uranus the total mass deployed on the balloon is the reactor (5 t), engine (3 t), refrigeration equipment (2 t), tankage and structures (about 8 t), and the balloon with its inflation plumbing (3 t), for a total of 21 tonnes (Table 1). The balloon is sized by the necessity of supporting the vehicle with full helium and hydrogen tanks just prior to departure, which requires 150 tonnes buoyancy (buoyancy data for both warm ambient atmosphere and pure hydrogen are given in Table 2). The balloon is shaped like a conventional hot-air balloon, 50 m in diameter at the widest point and 125 m long, with a

Table 1
Spacecraft Mass Model

Masses in Metric Tonnes

Component	Earth Depart.	Uranus Arrival	Uranus Departure	Earth Arrival
Aerobrake	5	(dropped)		
Balloon	3	3	(dropped)	
Liquid H_2			122	
Strap-On Tank	3	3	3	
Reactor	5	5	5	5
Engine	3	3	3	3
Refrigeration	2	2	2	2
Struct./tanks	5	5	5	5
Liquid ^3He			10	10
TOTAL	26	21	150	25

Table 2
Buoyancy of Warm Uranus Atmosphere and Pure Hydrogen

Buoyant Force in Metric Tonnes
(At 6 bar, 60 K Level; Balloon Volume = 10^5 m^3)

Interior Temperature (K)	Buoyancy of Warm Atmosphere	Buoyancy of Hydrogen
60	0	78.0
70	39.6	115.6
80	85.0	142.
90	113.	167.
100	136.	184.
120	170.	209.
140	190.	228.
160	213.	242.
180	227.	253.
200	238.	261.
220	248.	269.
240	255.	275.
260	262.	280.
280	267.	284.
300	272.	288.

number of separate internal cells. The internal volume is 10^5 m^3. If the balloon is filled with slightly heated ambient air, the temperature required for neutral buoyancy is 66 K. Flushed with byproduct hydrogen at ambient temperature (molecular weight 2.0 instead of 2.6), the lifting force is 78 t (a net buoyancy of 78 - 21 = 57 t). Thus slow, controlled cell-by-cell venting of waste hydrogen into the balloon can easily provide buoyancy even up to the point at which 57 t of liquids have been added to the tanks. Later, simply raising the hydrogen gas temperature to 85 K is sufficient to provide neutral net buoyancy with full tanks. The energy cost of maintaining buoyancy is trivial: the radiative loss from the 1.2×10^4 m^2 balloon surface is 1% of the available reactor power at 94 K, and becomes comparable to the reactor output only above 300 K.

The processing energy used in making 10 t of liquid ^3He is bounded by the amount of energy required to liquify the entire mass of gas containing this amount of product, 25 Gj/kg ^3He. Using rejected LH_2 to precool ingested gas with 80% efficiency, only 5 Gj/kg ^3He is required.

Liquifaction and ejection of hydrogen also removes methane, neon, and the heavy inert gases completely, leaving only pure helium with approximately solar isotopic composition. Cooling of the liquid helium to about 1.5 K allows superleak fractionation of superfluid ^4He from ^3He, up to about 1% ^3He concentration. Then simple distillation above 2.2 K (the temperature of the normal-to-superfluid transition of ^4He) will permit further enrichment of ^3He up to a concentration in excess of 99%. When the ^3He tank is nearly full, the liquid hydrogen byproduct can be accumulated instead of dumped, and the propellant tanks can be filled quite quickly (about 4 hours). The relevant data on hydrogen and helium are summarized in Table 3.

With a processing time of one Earth year, the total rejected heat load for this scenario is 1.6 MW, a small fraction of the reactor capability. Once tanks are filled, the balloon can be heated to 300 K to provide 289 t of buoyancy to lift the 150 t departure stage to about the 3 bar level, where the density of the ambient atmosphere is 1.4 times that at Earth's surface.

Departure from Uranus

A nuclear rocket with liquid hydrogen working fluid, with the nozzle throat regeneratively cooled by hydrogen, is able to deliver a specific impulse of about 1200 s. The delta V required for direct injection into an Earth-intersecting Hohmann transfer orbit (neglecting the use of Saturn and/or Jupiter swingbys) was shown above to be 20.1 km/s. The mass ratio given by the rocket equation is then 0.175, or 4.7 t of liquid hydrogen per tonne of payload. This uses 118 t of liquid hydrogen from the total available supply of about 122 t. Note that the exhaust velocity, gI_{sp}, is 58% of the mission delta V requirement, reassuringly close to the optimum.

Earth-Departure Mass

The mass that must delivered to Uranus can now be estimated (Table 1). The reactor, refrigeration equipment, engine, structure, and permanent tankage total 15 tonnes, and the empty strapon tankage adds another 3 t. The balloon and its associated shroud lines and gas tubes is also about 3 t, for a total payload of 21 t. The aerobrake for entry into the Uranus atmosphere is sized at 5 t (24% of the payload weight), for a total Earth-departure mass of 26 tonnes. Thus a single launch of a Saturn V-class HLLV into a Grand-Tour type trajectory (Jupiter and/or Saturn swingby), with no orbital rendezvous and no use of nuclear propulsion in near-Earth

Table 3
Data on Hydrogen and Helium

	Hydrogen	^4He	^3He
Normal Boiling Point (K)	20.4	4.2	3.2
Liquid Density at NPB (g cm^{-3})	0.08	0.13	0.08
Critical Temperature (K)	33.3	5.2	3.4
Critical Pressure (atm)	12.8	2.3	1.2
Onset of Superfluidity (K)	-	2.19	-
Melting Temperature (K)	13.9	-	-

space, can execute the mission.

Costs

A simple means of addressing costs is to calculate the amount of energy returned to Earth per unit of energy expended. For the lunar mining scenario this ratio is about 3:1. If the energy expended extracting gases from the lunar regolith is omitted (this is solar heat, and therefore arguably "free"), the ratio becomes about 250. Table 4 compares the energy use for the lunar and Uranus cases. Note that the outbound propulsive energy cost (and the attendant pollution of Earth's atmosphere by rocket exhaust products) is lower by a factor of 8500 for the Uranus case. The inbound propulsive energy cost (a negligible fraction of the total in both cases) is greater for return from Uranus by a factor of 100, and the total energy cost per kilogram of ^3He is less than 10^{-3} of the lunar alternative. The energy payback ratio for Uranus is 21000, even using conservative process energy figures.

A single mission of the type described here can return \$140 billion worth of fusion energy to near-Earth space. Marginal costs will be on the order of \$500 million each for the launch, nuclear propulsion system, and processing mission operations, of which about \$1 billion is front-end cost and the remainder accrues over the mission life. At a discount rate of 20% and a mission duration of 20 years the payback must be at least \$33 billion to justify the mission. For a discount rate of 10%, the return need only be \$6 billion. A demonstration mission the entire development cost of the Uranus-specific hardware and the propulsion system, on the order of \$5 billion, could easily be borne out of the profits.

Table 4
Energy Consumption Comparison
for Lunar- and Uranus-Derived ^3He

Gj per kg ^3He

Operation	Moon[a]	Uranus
Transportation from Earth	2180	0.25
Excavation	13	0
Conveyance/ Beneficiation	4	0
Heating Regolith	4100[b]	0
Compressor/ Refrigerator	67	5.[c]
Return to Earth	0.005	0.5
TOTAL	6364	5.75

[a] University of Wisconsin data.
[b] Using a ^3He concentration of 10^{-8} g/g, a heat capacity of 0.25 cal/g K, and delta T = 800 K, we calculate an energy use of $10^3 \cdot 10^8 \cdot .25 \cdot 4x10^7 \cdot 800$ = 80000 Gj/kg ^3He. The total would then be 85264.
[c] Using rejected LH_2 to precool the ingested gas stream with a thermal efficiency of 80%

Neptune is fully as suitable as Uranus for providing ^3He, but the trip times are much longer. Jupiter and Saturn have similar concentrations of helium in their atmospheres, but the energetic requirements for escape from them are much more severe. Also, temperatures near the tropopause are much higher, permitting other species to be present in the tropopause region and thus complicating the separation process.

Conclusions

If commercial production of electric power from fusion of ^3He with deuterium is shown to be technically feasible, then the preferred source for the ^3He is the atmosphere of Uranus. Because of the closeness of the Moon, the short round-trip time, and the great value of the other volatiles released along with helium during heating of lunar regolith, it still remains desirable to extract kilogram quantities of ^3He from the Moon for use in the development of commercial fusion technology. For operational use on the global scale, where hundreds of tons of fusion fuel will be needed each year, the most attractive source is the atmosphere of Uranus.

The two crucial items of new technology required for ^3He return from Uranus are a nuclear rocket stage using hydrogen as the working fluid and a "hot air balloon" filled with warm hydrogen to suspend the processing package in the uranian atmosphere. Processing of the ambient atmosphere to separate helium from hydrogen and methane and to separate the isotopes of helium can be done using a small subset of the equipment required to extract ^3He from lunar regolith. Among the features of the lunar scheme that may be omitted entirely are a) the need to mine 10^8 tonnes of dirt per tonne of ^3He, b) the need to beneficiate and size minerals, c) the energy needed to heat 10^8 tonnes of regolith to roughly 1000°C, d) the need for high process temperatures, e) the need to design around a two-week very hot day and a two-week very cold night, which creates severe temperature-cycling stresses and interrupts continuous processes, and f) the need to handle a wide range of reactive gases along with the ^3He. Ambient conditions on Uranus are very constant (about 60K and 6 bars atmospheric pressure), and the atmosphere is a mixture of hydrogen, helium, and methane. Methane is close to saturation at these conditions, and the atmosphere need be cooled by only 31K to initiate hydrogen condensation. The residual gas after hydrogen condensation is pure helium (nothing else is volatile enough to avoid condensation at 4K). Superleak separation and distillation of the helium isotopes then provide high-purity ^3He. Starting with a very cold gas containing 45 ppm ^3He is clearly much more attractive than abrasive dirt containing 0.01 ppm ^3He. The basic principle that leads us to favor Uranus over the Moon as a source of ^3He was well articulated by the famous American bank robber Willie Sutton (Table 5).

Table 5
The Willie Sutton Principle:
Formal Statement by the Original Author

"Why do I rob banks?
Because that's where the money is!"

-Willie Sutton

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A3.6 Results of analyses of a lunar-based power system to supply Earth with 20,000 GW of electric power

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ABSTRACT

The capacity of global electric power systems must be increased tenfold by the year 2050 to meet the energy needs of people on Earth. Solar power collected on the moon and transmitted to Earth by many microwave beams can meet these needs. Engineering and cost models indicate that the Lunar Power System (LPS) is economically robust and can be built at a faster rate than all other power systems. LPS uses understood technology. LPS implementation can immediately channel national and world R&D aerospace and electronics capabilities into completely peaceful directions and enable long-term human prosperity both on and beyond Earth.

RESUME

La capacité de l´ensemble global des systémes d'électricité devra être décuplée avant l´année 2050 pour satisfaire les besoins d´énergie de la population sur la Terre. L´énergie solaire recueillie sur la lune et transmise à la Terre au moyen de nombreux faisceaux microondes peut répondre à ces besoins. Des modéles d´ingénierie et de coût indiquent que le Systéme d´Energie Lunaire (SEL) est économiquement solide et peut être construit à une plus grande vitesse que n´importe quels autres systèmes énergétiques. Le SEL fait appel à une technologie bien connue. La mise en oeuvre du SEL peut immédiatement canaliser les capacités nationales et mondiales de recherche et développement aérospatiaux et électroniques dans des directions entièrement pacifiques et permettre une prospérité humaine durable à la fois sur et delà de la Terre.

1. 21st-CENTURY POWER NEEDS

The one billion people of the developed nations use approximately 6.7 kW/person to enable their high standards of living (kW is total power in kilowatts). On average, the other 4.3 billion people use less than 0.8 kW/person. These 4.3 billion other people are strongly motivated, primarily through the examples provided by the develeoped nations, to raise their standard of living. Meeting their needs will require a vast increase in the production of power. Total world power production, mostly thermal, is approaching 11,000 GW (G = 10^9). Approximately 30% of this thermal power is used to produce electrical power. World electric systems now generate 1,800 GWe ("We" is watts of electric power).

It is likely that 10^{10} Earthlings will inhabit our planet in 2050. If today's technologies and energy sources are employed, then the world will have to provide over 60,000 GW to support this population at the level the developed nations currently enjoy. Table 1 shows this is not possible. Either the primary energy source is inadequate (#1 to 7), the system will be interruptible and expensive (#8 and 9), or long-lived contaminants become a dominant concern (#10).

As technology advances, 2 kWe/person could sustain a higher level of affluence worldwide than now exists in the developed nations [Criswell and Waldron 1990]. Figure 1 is a simple model of the projected growth and revenue of an electric power system that could supply 20,000 GWe to the world in 2050. The top curve is the growth path the new system must follow. The bottom curve shows the annual cash flow if the electric power is sold to end users at 0.1 $/kW-H. Mature cash flow exceeds 15,000 B$/Yr or approximately 10% of the anticipated Gross World Product (GWP) in 2050. The accumulated gross return would exceed 840,000 B$. The new power system must also accommodate growth beyond 2050.

A good world environment can be provided if the source of the 20,000 GWe is clean, reasonably priced, and independent of the biosphere. Even if new technologies such as fusion and large space solar power satellites (Table 1: #11, 12, 13 and 14) are demonstrated early in the next century, adequate systems to produce and maintain them will be much larger than required for the Lunar Power System (LPS) (Criswell 1991). We maintain that the global needs can be met by providing solar power bases on the moon (Table 1: #15).

2. LUNAR POWER SYSTEM

P. Glaser (1977) introduced the concept of establishing huge solar power satellites (SPS) in space. The basic challenge is how to produce them economically. In addition, the magnitude of launch operations would lead to environmental contamination (NASA 1989, p. 73).

NASA funded studies on the production of SPS from lunar materials delivered to factories in space. M.I.T. examined the production and design of the factories (Miller 1979). General Dynamics developed systems-level engineering and cost models for the production of one 10-GWe lunar-derived SPS (LSPS) per year over a

Table 1 Characteristics of 20,000 GWe Global Power Systems

Power System	Maximum Energy Inventory (GW*Yr)	Annual Renewal Rate (GW)	Maximum Useful Power (GW)	Limiting Factors (@ $2*10^4$ GWe)	Deplete or Exhaust* (Yrs)	Pollution Products	Long - term Cost	Feasi-bility by 2050
Combustion power systems								
1. Bio-resour-ces	$<2*10^5$	$<1.5*10^4$	1,000	• Supply • Processing • Nutrients • Water & land use	<0.05	• CO_2 • Biohazards - methane - disease • Erosion	Up	Not
2. Coal	$<1.5*10^6$	0	$<2*10^4$	• Supply • Pollution	<100*	• CO_2 • Ash acids	Up	Not
3. Oil/gas	$<10^5$	0	$<5*10^3$	• Supply • Lost value	<30*	• CO_2 • Acids	Up	Not
Renewable terrestrial, non-combustion power systems								
4. Hydro-electric	$<2*10^4$	$<2*10^3$	$<2*10^3$	• Sites • Rainfall	<0.1	• Sediment • Flue water • Floods	Up	Not
5. Tides	0	<50	<50	• Sites • Input	<0.003	• Circulation	Up	Not
6. Geo-thermal	$>5*10^{17}$	$>5*10^8$	<100	• Good sites • Local depletion	<0.005	• Minerals • Ground cracking	Up	Not
7. Ocean thermal	$<1*10^6$	$< 1*10^4$	$<1*10^4$	• Cold & warm water • Build OTECs	<0.5 and <100*	• Waste heat • CO_2 store • Corrosion	Up	Not
8. Wind	0	$<1*10^6$	$<2*10^4$	• Diffuseness • Storage	<1	• Land use • Intrusive	Up	Not
9. Terres-trial solar power	0	$<1.8*10^8$	$<1*10^5$ 5% Earth surface 1% Eff. overall	• Building • Maintenance • Clouds • Power - storage - distribution	$>10^8$	• Waste heat • Production wastes • Induced climates • Land use	Up	Uncer-tain
Nuclear power systems								
10. Fission	$<1*10^6$	0	<500 (Present level)	• Acceptance • Life cycle & fuel costs	<0.03 and <100*	• Radioactive - fuels - parts	Up	Not
11. Fusion	$>1*10^9$ (D-T)	0	$>2*10^4$ Base load	• Feasibility •1st wall life • Build-up	>1,000s	• Radioactive parts • Waste heat	Up	Not
12. Fusion	0.001* to $1*10^8$ (D-He_3)	0 (moon)	$>2*10^4$ Base load	above & • Mining He_3	0 to <100*	& • Lunar atmosphere	Up	Not
Space power systems (SPS)								
13. Geo-SPS	0	$<X*10^4$ X - TBD	$<X*10^4$	• Geo-arc • Managing - satellites - shadowing	$>10^9$	• Shadowing Earth • Visible SPS • Debris	Up	Uncer-tain
14. Non-geo SPS	0	$>>1*10^6$	$>1*10^5$	• Production & repair •Use on Earth	$>10^9$	• New objects • Stray microwave	Down	Uncer-tain
15. Lunar power system	0	$>1*10^6$ (@ 10% effic.)	$>1*10^5$	• Moon's area • Power use on Earth	$>10^9$	• Stray microwave	Down	Prom-ising

period of 30 years and concluded that LSPS would likely be less expensive than SPS after the production of thirty 10-GWe satellites (Bock 1979). The SPS and LSPS studies raised basic questions. Why transport materials from the Earth or the moon to build large platforms in space? Why not build the solar power collectors and transmitters on the moon from lunar materials?

The moon is a far larger platform than any that can be built in space. The same surface of the moon always faces the Earth. Can we build the solar collectors on opposing limbs of the moon, from the local materials, and beam the power from the moon directly to Earth?

Those questions lead to the conceptualization of the LPS (Waldron and Criswell 1991, Mueller 1984).

The major elements of LPS are shown in Figure 2. The basic system consists of pairs of power bases (1 & 2) on opposite limbs of the moon as seen from Earth, and rectennas on Earth (3, 4, 5 and others). The rectennas convert the microwaves to electric power. Hundreds to thousands of low-intensity microwave beams would be directed from each lunar base to the

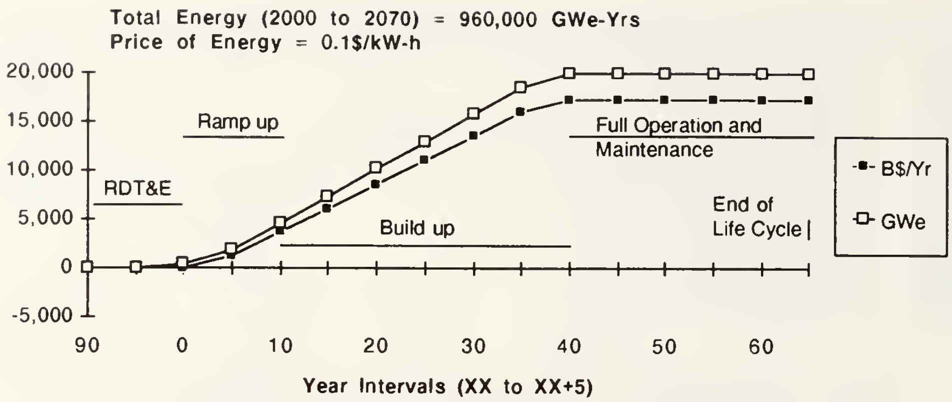

Figure 1 Capacity and Revenue of a New Planetary Power Sources

rectennas on Earth and associated with facilities and vehicles in space (6). A microwave power beam is only created, on request, to feed power to a designated rectenna. The beam is shut off when the need for power at that rectenna ceases. Beams would not be swept across the Earth from one rectenna to another.

A given lunar power base would project energy for 12.5 days out of each lunar month. A given terrestrial rectenna receives power approximately 30% of the time when the moon is above its local horizon. This basic LPS requires power storage units on the moon or on Earth in order to provide continuous power at Earth.

The basic LPS can be extended to provide continuous, load-following power to rectennas. Relatively low mass and simple microwave reflectors (#7), in mid-altitude, high-inclination orbits about Earth, can redirect microwave beams to rectennas that can not directly view the moon. The microwave reflectors can eliminate the need for long-distance power transmission lines on Earth. Also, additional sunlight can be reflected by mirrors (#8) in orbit about the moon to bases #1 and #2 around lunar sunrise and sunset and during eclipses. Each limb base can be augmented by a set of photovoltaics just across the lunar limb. Power lines would connect these cells to the transmitters on the Earthward side of the moon.

Figure 3 provides a sequence of five progressively closer-in views of a power base, such as #1 in Figure 2, and the thousands of power plots that constitute one power base. View #1 of Figure 3 shows an area of the limb of the moon, as seen from the Earth, that encompasses three power bases (*pb*). View #2 is from high above that lunar limb. This view reveals that each base is elliptically shaped and approximately six times longer along a moon–Earth line than its apparent diameter as viewed from Earth.

View 3 is a side view of a vertical cut through base *pb*. It shows a few of the thousands of power plots. View 4 is in the plane of the vertical cut, looking toward the moon from the Earth. It shows that the power plots are arranged within *pb* so that the microwave reflector grids associated with each power plot appear to fill a circle 10 to 100 km in diameter. That circle of reflector grids forms the huge, segmented phased-array antenna that beams energy back to Earth.

View 5 is a closeup side view of one power plot, the black one in View 3 and shown also near the bottom-center of View 4. The power plot is composed of three major elements: solar converters, microwave subtransmitters, and a microwave reflector grid. The solar converters provide electric power through a grid of buried wires to many solid state microwave sub-transmitters. The transmitters illuminate the microwave reflector grid with many sub-beams, and the grid directs each sub-beam toward Earth.

The characteristics of the three elements are considered next. The solar converters will be thin-film photovoltaics formed on thin sheets of lunar-derived glass. Only moderate conversion efficiency is needed (>5 to 10%). The moon is a far better location for intrusive, large-area solar converters than is Earth. This is because on the moon sunlight is completely dependable and the collectors can have <0.1% the mass per unit area of a terrestrial photoconversion array. Power is collected locally by a grid of wires that is buried under the lunar surface.

The power is delivered to hundreds to thousands of sets of individually controllable solid state microwave sub-transmitters. Each sub-transmitter sends a small sub-beam toward the microwave reflector grid at the opposite end of the power plot. Power regulation and limited power storage capability can be provided. Some components of the sub-transmitters might be imported from Earth.

Each microwave reflector grid is constructed of foamed or tubular lunar glass beams that support a microwave reflective surface consisting of a cross grid of glass fibers coated with a metal such as aluminum or iron. The segmented aperture (View 4 in Figure 3) could be a few kilometers across for high frequency beams

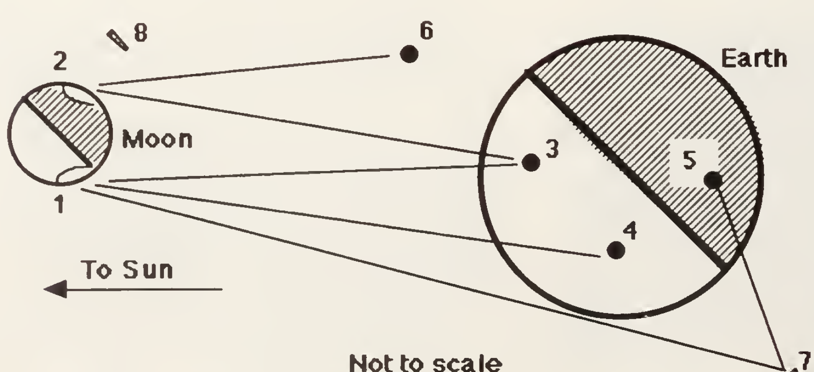

Figure 2 Major Elements of the Lunar Power System

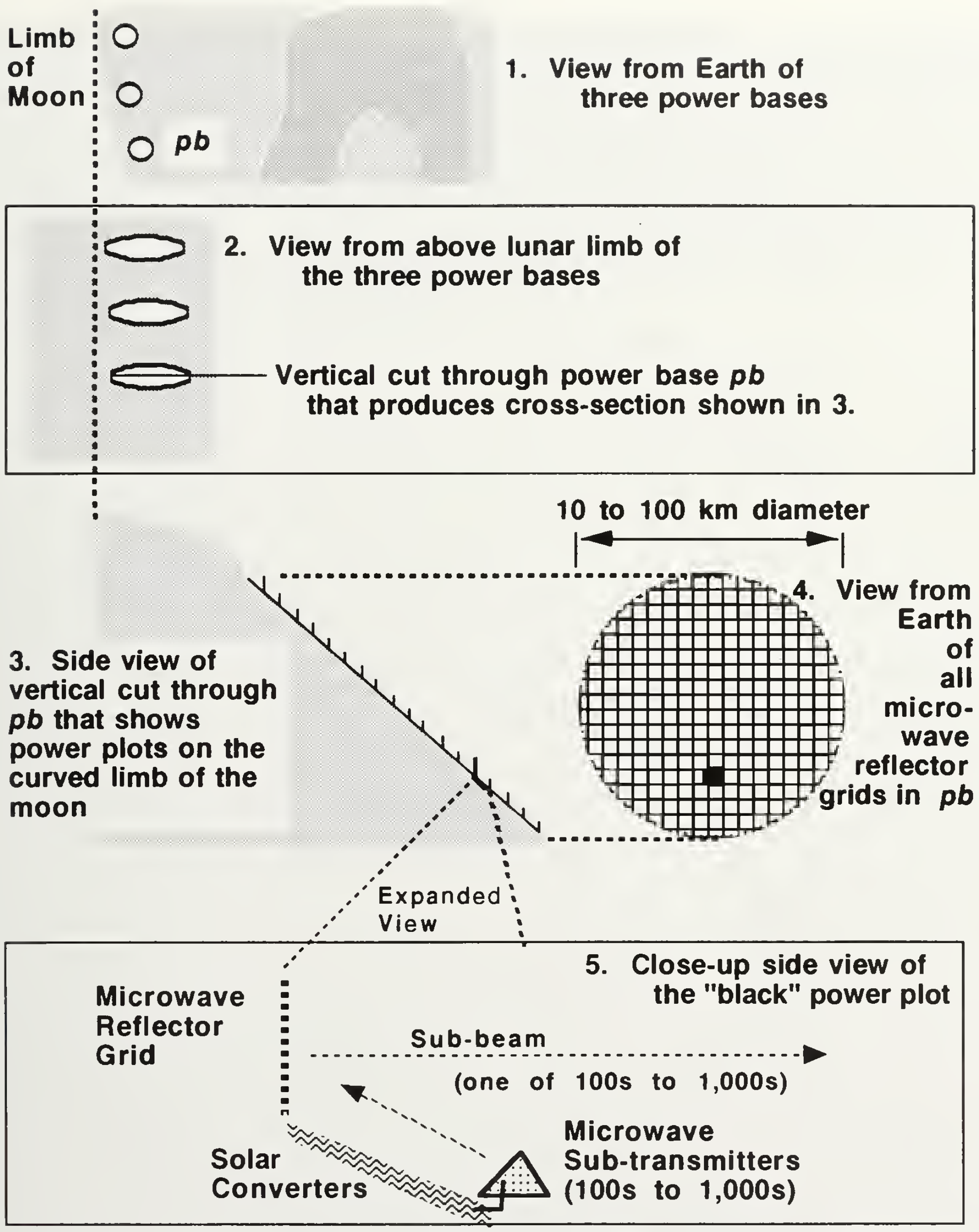

Figure 3 Progressively Closer Views of a Lunar Power Base

(< 1 cm) transmitted to space facilities, and the order of 100 kilometers across for longer wavelength beams (10 cm) transmitted to Earth. The enormous segmented antenna is possible because the moon is extremely rigid and non-seismic, the antenna always faces Earth, the antenna segments can be constructed of local materials, and the cost of each antenna is shared by thousands of beams of high total power. Thousands of coordinated sub-beams from all the power plots produce one of the power beams depicted in Figure 2. The beams are convergent (near field), but slightly defocused, like a spotlight, to distances (=D*D/*w*) many times that of the Earth–moon distance. D = 30 km to 100 km and wavelength= *w* = 10 cm.

Each LPS beam can be fully controlled in intensity across its cross-sectional area to a scale of a few 100 meters at Earth. This allows the LPS beams to uniformly illuminate rectennas on Earth that are larger than 200-300 meters across. The microwave beams projected by the LPS should have very low sidelobe intensity and no grating lobes. The stray power level should be very low and incoherent. LPS could probably operate economically at a lower power density (~ 1 milliwatt/cm^2) than the leakage allowed under federal guidelines (5 mW/cm^2) from microwave ovens used in homes. A beam intensity of 23 mW/cm^2 produces little sensible heating in animals The stray, incoherent power levels of the microwaves on Earth of a 20,000 GWe LPS may be less than the power per unit area thermally radiated by a human or the Earth itself. If so, the power-beaming system can be completely safe. LPS beams can efficiently service rectennas on Earth after they are more than 200 meters in diameter and several 10s of megawatts in power output. Thus, as rectennas are enlarged beyond a diameter of 200 meters, the additional growth can be paid for out of present cash flow derived from power sales. Smooth growth in capacity from a small starting level provides fundamental financial advantages over all other major power systems.

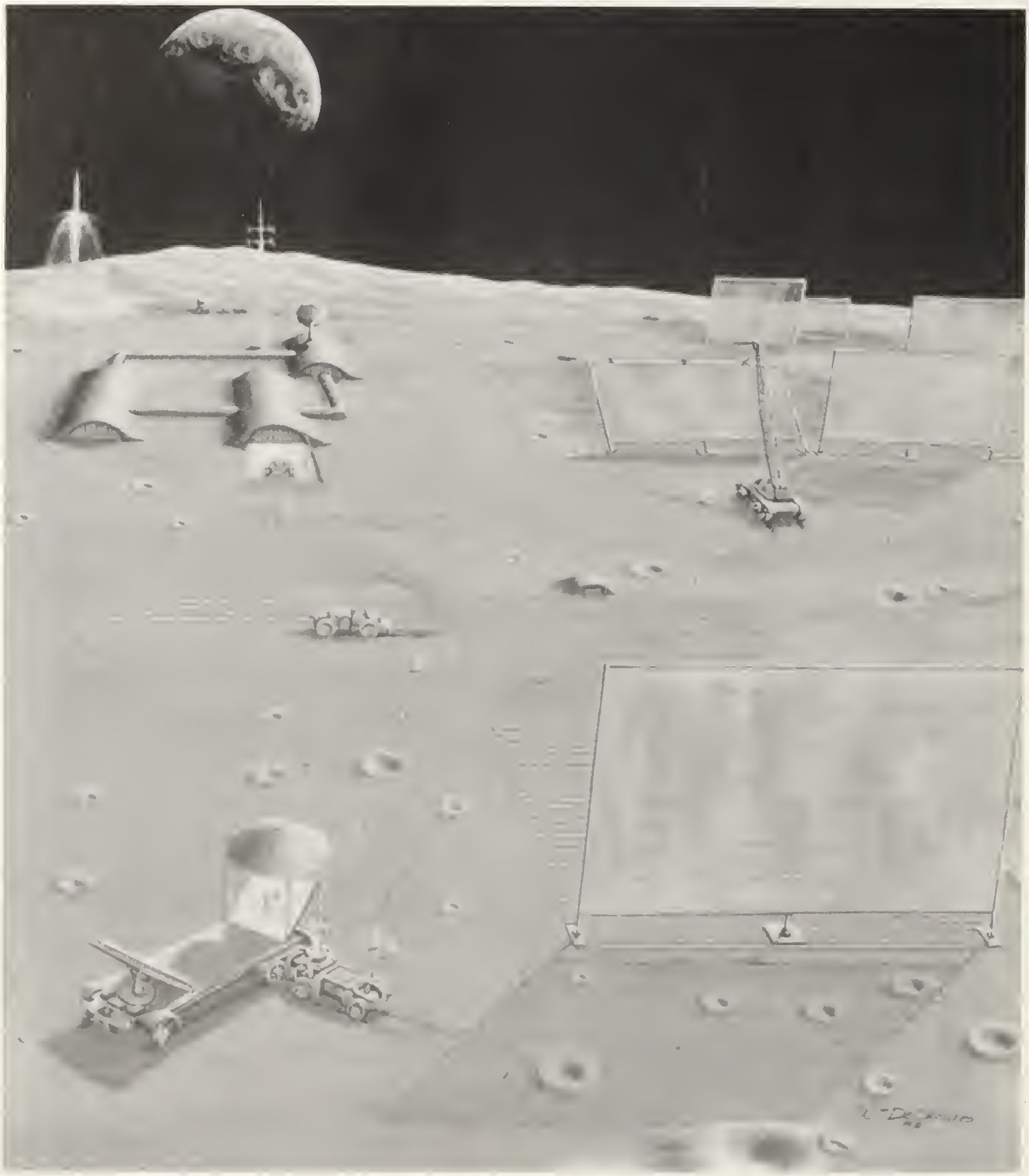

Figure 4 Artist's Concept of the Construction of a Demonstration Lunar Power Base

Figure 4 depicts the operations needed to construct a lunar power plot (De Generes and Criswell 1983). Several tractors are shown smoothing the lunar surface, extracting fine-grained iron, burying wire for power collection, and laying down glass sheets under which are layered solar converting thin films of moderate efficiency (5 - 10% are adequate). In the foreground is a mobile glass processor that melts lunar soil to produce foamed glass supports, fiberglass, and glass sheets. The supports and fiberglass are used to make the microwave reflectors. One reflector is shown being erected. Solar electric power is provided to sets of microwave sub-transmitters that are buried under the mound at the Earthward end of each power plot. Note that the Earth remains in the same general position in the sky at a given base. Most of the emplacement operations are conducted by a fleet of relatively small and independent machines that move from one construction area to another. The rate of installation of new power is proportional to the number of machines and their productivity. Section 3 describes costs and profits scaled to deploying sufficient machines that emplace 50 GWe/Yr of power; section 4 presents lower emplacement rates.

3. RESULTS OF MODELS

Engineering and life-cycle cost models of the LPS have been developed for an LPS that meets the power profile shown in Figure 1 and that delivers approximately 960,000 GWe-Yr of energy to Earth between the year 2000 and 2070 (Criswell and Waldron 1990, NASA 1989: see p. 84-96). Approximately 400,000 tons of production equipment (miners, materials processors,

construction units, habitats, etc.) are taken to the moon between the years 2000 and 2040. Half of the materials arrive the first ten years. Components, supplies, personnel, and process expendables constitute the additional 600,000 tons transported to the moon on a steady basis between 2000 and 2070. Approximately 18,000 tons of facilities are required on the moon for an average working population of 4,000 people. In low lunar orbit , 12,000 tons of facilities support approximately 340 people in logistics and production of lunar orbital reflectors (#8 in Figure 1). An additional 170,000 tons of facilities in low Earth orbit support logistics. They also manufacture and maintain the Earth orbital reflectors (#6 in Figure 1).

Averaged over the entire program, the delivery of one GWe-Yr of energy to Earth requires the export of four tons of mass from Earth to the moon. The LPS pays back its electric energy of production in five days. Over the 70 years of power production, the LPS will return approximately 840,000 B$ (B= 1^*10^9) of net profit if the power is sold for 0.1 $/kWe-H. Total LPS costs, non-discounted, over the 80-year period from 1990 to 2070 are 18,200 B$. This is an enormous total. However, LPS provides such a large return that the energy cost is only 0.002$/kWe-H.

Figure 5 presents the annual revenue and expenditures for all LPS operations from 1990 to 2015. The model of LPS assumes that all costs are included. The costs are divided into five-year segments and the annual levels (B$/yr) are presented for four categories of expenditures: Transportation (Trnsp.), Lunar Base (LunB), Earth Facilities and Rectennas (EF&Rec), and Lunar Power System elements (LPS). The five-year period of research and ground-based demonstrations costs 100 B$. The next five years of development, production, and start of operations of all flight elements costs approximately 500 B$. The elements in this interval are so small that they are barely resolved in Figure 5. It is extremely important to note that after the year 2000 the construction of rectennas dominates all costs of the LPS program. Total cost of rectenna construction and operation between 2000 and 2070 is approximately 18,000 B$. Space operations total only 1,800 B$.

The system will grow to provide Earth with 20,000 GWe by the year 2040. This system would begin at the demonstration stage (50 GWe/Yr) and build to the maximum emplacement rate (560 GWe/Yr) over the next 30 years. The LPS would be in full operation 40 years after start of construction. This model assumes that maintenance of the LPS requires 50% of the expenditures to build it. The electric energy payback time of five days for the lunar installations is much shorter than any other electric power system.

Electric energy is forecast to cost less than 0.002 $/kWe-H in non-discounted dollars. Because rectenna construction dominates all costs, it is reasonable to anticipate such a low projected cost for electric energy.

In this model, the revenue from the sale of power at 0.1 $/kWe-H on Earth would begin by 2002. Revenue would exceed expenditures within the third year of power production. Within the next three years, the enterprise pays off all previous investments. Annual revenues increase steadilv

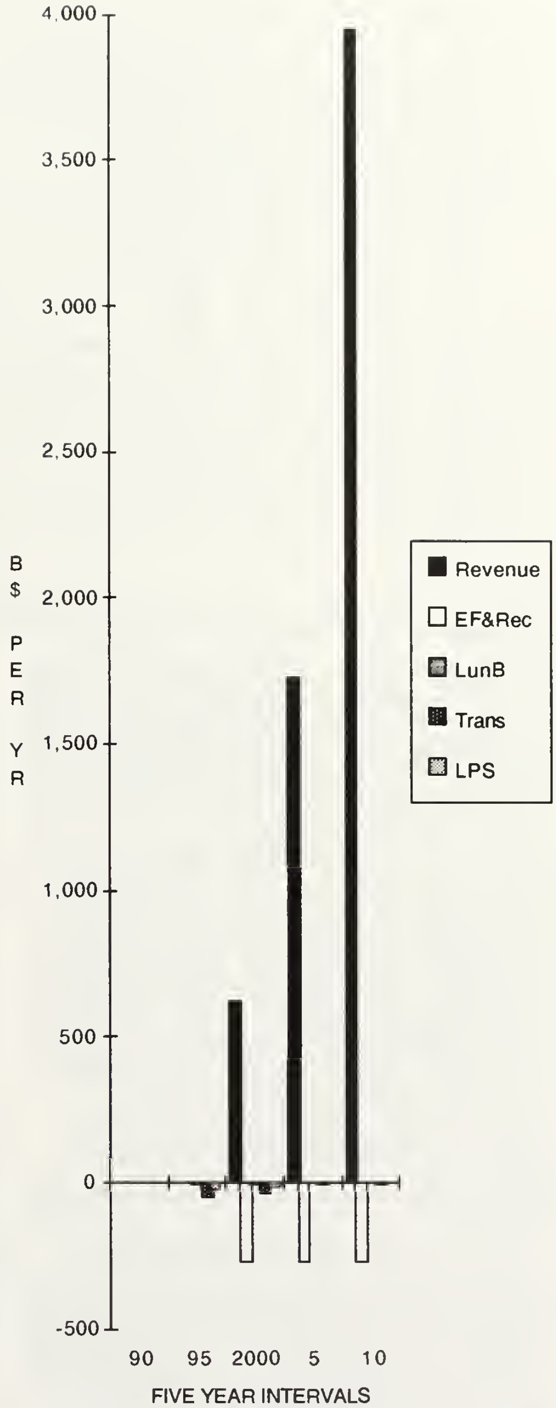

Figure 5 Annual Revenue and Expenses

until the maximum power production of 20,000 GWe is achieved in 2040 and the net annual profit exceeds 15,000 B$/Yr. An LPS base can be maintained indefinitely. As technology advances, an LPS base can be upgraded to a much higher power level while it is operating. The year 2000 date for start of lunar operations is arbitrary. Delays simply lose profits, defer creation of new markets, push back global environmental benefits, and postpone permanent, self-sustained occupancy of the moon.

Figure 5 clearly shows that LPS can provide a very attractive return on investment under the baseline model. Figure 6 shows the effects on LPS profitability of increasing and decreasing the cost of installing LPS (cost multiplier CM applied to all costs between 1990 and 2040) and of a higher

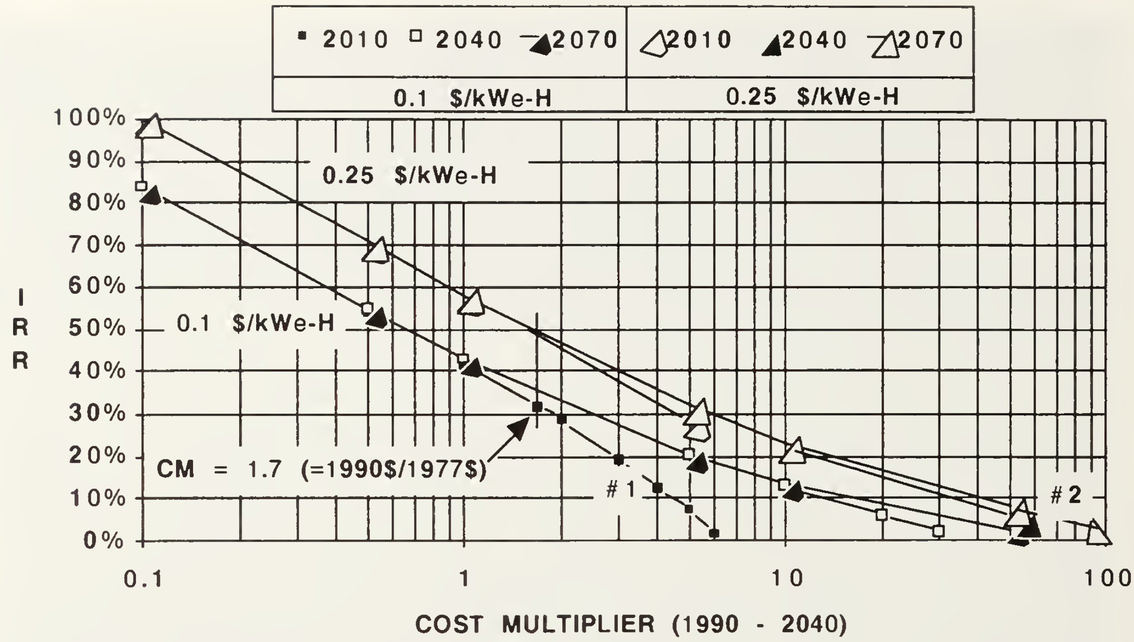

Figure 6 **Internal Rate of Return (IRR) vs Mulitplication of all Costs (1990 to 2040)**

selling price for power. Internal rate of return (IRR) is used to measure the profitability of LPS. IRR is the annual interest rate a bank would have to pay an investor between the start of profitability and the year 20XX (dates in box), given the profile of investments (expenditures) shown in Figure 5, to match the revenue in Figures 5 & 1.

Figure 6 contains six distinct curves that merge into two lines for CM < 1. The bottom set of three curves applies for selling power at 0.1 $/kWe-H, and the top set of three curves to selling power at 0.25 $/kWe-H. The studies by General Dynamics were based on 1977 dollars. Prices increased by a factor of approximately 1.7 between 1977 and 1990. The reference case has CM = 1.7 and the selling price of power = 0.1 $/kWe-H. For the reference case, the average IRR = 31%/Yr between the start of profitability in 2005 and the year 2010. IRR increases to 35%/Yr when the period for return on investment is extended through the two intervals 1990 to 2040 and 1990 to 2070.

Curve #1 (black squares) applies to the reference case for the interval starting with the year of profitability and extending to the year 2010. Note that this IRR decreases as CM increases and crosses IRR = 0 near CM = 6.2. This means that if costs of the reference case rise by a factor of 3.6 (= 6.2/1.7) then the short-term IRR goes to 0. However, revenues are so large that over the longer time periods of 1990-to-2040 (open squares) and 1990-to-2070 (dark triangles) the IRR is 18%/Yr at CM = 6.2.

If the world relies on conventional power sources, then the price of electricity will likely rise to 0.25 $/kWe-H or even higher (NASA 1989). Note the upper curve at CM = 1.7. If power from the reference LPS is sold at 0.25 $/kWe-H, then IRR = 48%/Yr for the period from start of profitability to 2010 and rises to 50%/Yr when the return period is extended to 2070. Higher selling prices greatly increase the financial robustness of LPS. Note the end point of curve #2 at CM = 100. IRR is still positive at both 2040 (IRR = 0.7%/Yr) and 2070 (IRR = 4%/Yr) even though costs have increased by 5900% or a factor of 59 (= 100/1.7) compared to the reference case.

LPS is very likely to be more robust financially than discussed above. Figure 5 shows that the major cost element of LPS is construction of the rectennas on Earth. The reference case assumes rectennas cost 200 M$/km^2 to construct and that they operate at 23 milliwatts/cm^2. Rectenna costs should go down as more are produced, and some might be operated at a higher power density. CM could be substantially less than 1.7. It is reasonable to anticipate IRR > 40%/Yr for 01.$/kWe-H and IRR > 60%/Yr for 0.25 $/kWe-H. If rectenna construction costs decrease, then R&D and space expenditures could increase by a factor of 60 (0.1 $/kWe-H) to 300 (0.25 $/kWe-H) without significantly degrading the financial robustness of the LPS.

As soon as large transmitting apertures are established on the moon, they can begin to provide many different beams of low power, and each beam can be converged to a few hundred meters in diameter. Thus, rectennas on Earth can initially be small, the order of 10s MWe, and then grow smoothly in power output and diameter. Their growth can be paid for out of current cash flow. All other large power systems require a decade or more of up-front investment before income is generated.

No other global investments on the horizon could provide such enormous returns over many decades. In addition, LPS should not have the hidden environmental costs of conventional power systems.

4. STARTING SMALL

The LPS model was used to estimate the costs of establishing much smaller power systems. The results are presented in Table 2 (Case #1, one GWe; Case #2, ten GWe; and Case #3, 100 GWe). The model assumed a ten-year period of R&D, a three-year deployment of all equipment, and then ten years of steady-state emplacement of power beaming capacity from the moon to the Earth. These models draw on the analyses by General Dynamics that were scaled to emplace 10 GWe/Yr of SPS. Several costs, such as transportation, do not scale linearlv to lower rates of power

Table 2 Parameters of Smaller Bases

Cases	# 1	# 2	# 3
GWe installed over 10 Years	1	10	100
GWe-Yrs of energy	5	50	500
Gross Revenue (B$) (@0.1$/kWe-H)	4.383	43.83	438.3
Net Revenue (B$)	-55.7	-46.8	194.9
Total Costs (B$) (sum 1+2+3)	60.1	90.6	243.4
1. R&D (B$) (sum *a+b+c+d*)	42.4	50.9	85.5
a. LPS Hrdw	*10.7*	*10.7*	*10.7*
b. CNSRT. SYST	*1.1*	*2.9*	*10.1*
c. FACILITIES & EQ	*5.1*	*10.0*	*29.9*
d. TRANSPORT	*25.5*	*27.4*	*34.7*
2. Space & Ops (B$)	17.2	34.2	102.5
3. Rectenna (B$)	0.6	5.5	55.4
$/kWe-H	1.37	0.21	0.06
Moon (tons)	2,284	6,194	21,552
Space (tons)	974	2,680	9,677
People (moon & space)	30	85	300

emplacement. Consider the results as encouragement for further work. Case #3 is closest to the situation modeled by Bock (1979).

R&D is the dominant expense for final power levels less than 100 GWe. R&D that is unique to the equipment to install LPS on the moon is small, 15–20 B$, relative to the overall expenditures required to establish a lunar base and the associated transportation system. Costs of Space Equipment and Operations increases sharply between 10 and 100 GWe final installed capacity. The cost of power drops sharply as the installed power increases. Between 10 and 100 GWe of final installed power, the net cash flow goes positive (price of power 0.1 $/kWe-H). Net expenditures might be less than 100 B$ by the time positive cash flow begins. Power could sell for much greater prices to customers off Earth.

There are many possibilities for reducing costs as cis-lunar space becomes energy rich. LPS can support experimenters, supply power for space logistics, and power isolated Earth receivers. Lunar materials can be used to reduce the costs of transportation and logistics and to build portions of the emplacement systems.

5. ORGANIZING THE LPS PROGRAM

To develop LPS, three types of investors are anticipated: governments, consortia, and local organizations. Between 1990 and 2000, government programs will pay for the development and initiation of the transportation elements and the lunar base. Between 1990 and 2000, expenditures can be comparable to present United States government expenditures in aerospace products for the U. S. Department of Defense and NASA. LPS can provide an excellent, peaceful focus for the present defense- and technology-related organizations of the space-faring nations.

A national or international consortium can be formed to develop, procure, and implement the elements for LPS production and do the RDT&E for rectennas. After the year 2000, this consortium can conduct all off-Earth operations. Between 2000 and 2005, it would begin receiving a net positive revenue from the sale of power on Earth. More than one consortium can be formed. Many lunar bases are needed.

Rectenna R&D, both for rectennas and their means of production, can involve all the nations of Earth. Rectennas can, as appropriate, be constructed, operated, and paid for by private groups, cooperatives, and countries. Virtually all the costs of rectenna production will be covered by current cash flow. The major challengens are startup costs and public confidence in LPS.

6. LPS SUMMARY

LPS can be developed expeditiously. We have sampled the moon and possess sufficient understanding of the moon to make many uses of its resources. Costs of the initial stages of LPS can be significantly reduced if done with the emplacement of a manned lunar base. Small demonstration units can quickly provide confidence in our abilities to emplace and operate LPS.

The equipment to implement LPS has a very low mass per unit of delivered power compared to all other systems and can emplace the power system rapidly (Criswell and Waldron 1990, NASA 1989). Advances in technology can sharply decrease expenditures and increase the emplacement rate of power for all phases of the LPS program. Many of the key technologies for LPS are developing rapidly because of their value in the terrestrial marketplace. Thin-film solar arrays, solid state microwave electronics, and microcomputers are key examples.

To supply the Earth with 20,000 GWe of power by the year 2050 we must look beyond the confines of Earth. We must look to the energy production of the sun and the already known natural resources of the moon. LPS appears to be the only option for providing large-scale power systems in the next century without severely distorting the world economy and ecology.

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SPS 91

A3.7 Economics analyses of lunar resources for solar power satellites

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Several studies have determined that almost all, eg. 95 to 99 %, of a Solar Power Satellite (SPS) could be produced from lunar-derived materials. It is argued that in view of the Moon's much smaller gravitational potential, transportation costs to deliver lunar materials to geosynchronous orbit would be much less than to deliver materials from the surface of the Earth to geosynchronous orbit. Very preliminary cost calculations tend to substantiate the possibility of reducing SPS cost via the lunar materials route, but more substantial calculations are needed to assess the economic viability of lunar resources and transportation operations for SPS. The proposed paper will describe the appropriate methods, and illustrate them with representative calculations using best available estimates for key economic parameters.

This paper will extend results of an earlier paper (1989), investigating economics of lunar resources for SPS, and also extending methods and results of a 1990 paper (presented at Case for Mars IV) on economic factors relating to space settlements. In the first reference, I used a 120-parameter static input/output model of a space transportation network. Significant additional understanding can be derived by extending the input/output model to include mining and manufacturing operations on the lunar surface and in GEO orbit and by making it dynamic in order to model the build-up of the lunar industry that would produce the SPS materials.

The key issue here is productivity. The Case for Mars paper developed a rudimentary dynamic model (12 parameters) which indicated that very large advances in productivity, meaning major advances in space robotics, are necessary. Our lunar base needs to have productivity about like a Japanese automobile factory.

For the proposed paper, I plan to extend the Case for Mars IV model to about 50-75 parameters, merge it with the transportation network model, examine some transportation alternatives (rockets vs. mass drivers), examine productivity factors, eg. manhours per pound of manufactured products, and consider different mixes of Earth vs. lunar products.

A4.1 The Environmental impact of SPS: A social view

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ABSTRACT

The time is coming to promote Solar Power Satellites (SPS) as one good alternative to fossil fuel burning. We strongly suspect that the impediments to the implementation of SPS will NOT be technical, they will be political and social. Today, every means of generating electricity is being attacked by somebody. Of course, many concerns about power generation are legitimate. Coal burning does pollute the air and promote acid rain and nuclear power does generate difficult to store wastes. People talk about "risks" of this or that. What they should be discussing is "risk-benefit". No means of generating power (or doing anything else in life for that matter) is without some risk. The real question is, does the benefit of having electricity from a given source out-weigh the risk? **For SPS, it is very important to make sure that the environmental issues and possible public concerns are explored as much as possible before SPS comes to the attention of the general public.** To do this, we must first gather from the experts, information on what are the possible hazards, both real and perceived, for SPS. All concerns must be addressed. Experts must be unified on explanations of what is and is not a hazard, why it is or isn't and what to do about real hazards. This paper will address issues such as the environmental impact of microwave beams proposed from SPS to Earth, the space debris hazard posed by and to SPS, and other environmental issues. We will explore, not only the purely technical aspects of this, but also, some "what-ifs" that people are so good at worrying about and some ways to successfully market the SPS idea. It is no longer enough for experts to simply say "trust us" there is no hazard.

+president and senior physicist of ETM, member AIAA

RESUME

L'éducation de la société est à la charge des concepteurs du SPS. Et la prise en compte de cette tâche est une condition sine qua non du succès du projet.

Du temps et de l'argent doivent être réservés de façon significative à :

- la recherche sur les problèmes d'environnement et de santé engendrés par le projet SPS afin de bien évaluer les rapports risques/bénéfices.
- l'éducation du public, et les façons d'inclure le public dans les décisions sur les nouveaux systèmes de production d'énergie, dès le début.

Les conséquences du projet SPS sur l'environnement ainsi que les conditions de sécurité doivent être évaluées avec autant de rigueur que les aspects techniques, faute de quoi ces systèmes n'ont aucune chance d'aboutir.

Introduction

This is not a technical paper. It is meant to address what I believe are going to be some of the societal issues involved in getting public acceptance of SPS. Every power generation system has issues like these. It is imperative to address these issues squarely and begin to get the public more educated and more involved in the decision making process.

If you think getting public acceptance of SPS will not be too difficult, do I have news for you. In the book, The Microwave Debate [1], there is an outline of what went on at a public hearing on whether HBO should be allowed to install a microwave uplink facility in Rockaway Township, NJ in 1980. The people living near by had all kinds of worries about whether microwaves (in the intensity range of 0.005 mW/cm^2) would effect them.

One of the world experts on the effects of microwaves on humans, Dr. Herman Schwan, was called to testify at these hearings. At one point during the testimony, the issue of his qualifications came up. He was a specialist and as such did not do lab work. He argued with the chairman, that any expert witness could be disqualified with such arguments as no one scientist was expert in all aspects of biophysical research. He angrily left the hearings after being accused of suppressing information on the effects of microwaves at the 10 mW/cm^2 level.

After months of hearings and thousands of dollars spent, HBO withdrew their request to site the facility in NJ.

The HBO problem represents the general tone of public skepticism and the type of debate that can get going over just about any installation that people are fearful of. As with other issues of public hazards, such as where to put spent nuclear fuel or where to site a new landfill, much of the opposition is

emotional or political rather than technical. The HBO case highlights what the proponents of the SPS (and any other new power generation system) are up against. The public will have to be educated and included in any decision to build an SPS. **Furthermore, it is the duty of the proponents and designers of SPS to educate people. In the past, this duty has often been shirked by the technical community partly because it is a daunting task (especially in the USA where science education is so poor) and partly because such efforts cost money. However, if the effort is not made, all SPS plans are going to fall flat.**

The Concept Development and Evaluation Program for SPS (CDEP)

In the mid 1970's, the department of Energy and NASA teamed up and looked into the environmental impact of SPS. This group was called the Concept Development and Evaluation Program, or CDEP.[2] A brief summary of this information was given by Dr. Glaser at the Solar Power Satellite conference in 1986 [3]. The issues CDEP addressed were as follows:

* Health and biological effects of microwave radiation
* Nonmicrowave effects on health and the environment
* SPS effects on the atmosphere
* SPS effects on communications systems due to ionospheric heating
* Electromagnetic systems compatibility

The CDEP groups did a very good job at ferreting out possible problems. Their more definitive findings included:

* SPS interference with other communications and electronic systems.
* heating of the ionosphere

In other areas, the CDEP findings were less definitive. Their conclusions were often that "this needs more research, but it is probably not a problem". Since there was no further funding, most follow up research has not been done.

They did conduct a large public outreach project to find out public opinion of SPS [7]. The main public concerns raised were

* <u>possible military use of SPS</u>
this item can probably be handled by education of the public

* <u>vulnerability of SPS</u>
it will be difficult to convince people this is not a problem, since, like other large power plants, SPS DOES present a vulnerability problem

* <u>dependence on centralized power systems</u>
this concern could be addressed by making the SPS power company a public co-operative. Thus if SPS profits, so do all the co-operative participants. I do think that reliance on any one power generation system would be a mistake. Look at the bind we are in with oil.

Earth bound solar power generation for individual homes and communities should be developed. Perhaps spinoffs from SPS would be useful to that effort.

* <u>biological effects of microwaves</u>
This is going to be the most difficult concern to deal with. As we will see the information is scattered and conflicting.

What I'll do in this paper is talk about some of the issues of safety and environmental impact. I'll be playing "devil's advocate" in the sense of trying to bring you to an awareness of the problem of selling SPS to the public. Many of these issues relate to an SPS for power beaming in space as well as to an SPS for beaming power to Earth.

Biological effects of microwaves

There is a vast quantity of literature on this subject. There are all sorts of marginal experiments and studies. There are conflicting reports and much of the work has been done by the military and public trust of this work is marginal. The following items are taken from The Microwave Debate and Biological Effects of Microwaves [1,4]. There is much more information than can be presented here. The Microwave Debate is a good review of the social issues, whereas Biological Effects of Microwaves summarizes all the scientific data up to 1976.

* As a mater of definition, most scientists consider "Microwaves" to be EM radiation in the range 300 to 300000 MHz (10 to 100000 MHz in the USA)

* microwaves are nonionizing radiation. We all take this for granted, but the average citizen does not understand this. The energy of an SPS photon of microwave energy is $E=hf= 4.136 \times 10^{-15}$ eV x 2.45×10^{9} Hz = 1.0×10^{-5} eV. For comparison, the binding energy of the electron on a hydrogen atom is 13.6 eV.

* The current US standard for microwave exposure is 10 mW/cm^2. This standard is not mandatory.

* In the 1930's microwaves were used medically for heating the body. This heating was supposed to have various curative effects.

* In the 1950's, physicians and others began to look into possible problems of over exposure to microwaves.

* The recognized and fairly well studied problems arising from over-exposure are due to heating (thermal effects). It is easy to show that small animals exposed to power levels above 100 mW/cm^2 can be killed (in just a few minutes) by over-heating. Heating is accomplished as follows: microwave irradiation is basically the application of an external (alternating) electric field. An alternating field can cause oscillation of free charges and can affect molecules, such as water, that have asymmetrical charge distribution. In other words, induced dipoles arise. These dipoles tend to rotate in the oscillating field, and the friction with other media during this rotation causes heating.

* In addition to simple heating of bulk material, it has been postulated (Vogelhut, 1970 referenced in [1]) that "water bound in macromolecules and subcellular structures may be considered similar to doped ice layers, which "melt" due to microwave energy absorption". If this could happen, it would have serious biological consequences. As far as I know, this idea has not been tested. But it gives you an idea of how good people are at thinking up the worst.

* There is much debate over the existence of non-thermal (or athermal) effects. The existence of athermal effects would mean that even very low power levels of microwaves could be suspect. Although microwaves cannot ionize atoms or break molecular bonds, they can set molecules into excited states. This sort of excitation can possibly change the orientation of molecules, which in turn can cause biological damage. Various studies have reported damage of animal testes and cataracts caused by microwaves. However, there is still debate as to whether these are thermal effects or athermal and how the data can be applied to humans. Other possible athermal effects have been investigated with respect to the nervous system. Some Soviet authors have reported that microwave irradiation at power levels below 10 mW/cm^2 cause various behavior modifications. Although western scientists tend to shrug off the Soviet work as not repeatable, some of it definitely has been repeated. It has been shown that conditioned responses in animals (such as rats) can be affected by low power level microwave irradiation. According to their own data, the Soviet standard for microwave exposure is 0.01 mW/cm^2 as compared to the US standard of 10 mW/cm^2. Another documented phenomenon is perception of microwaves as an audible click.

One test for athermal effects drew a lot of attention in the 70's. This was an experiment with chimps irradiated with 0.5 -1 mW/cm^2 (2.2 -4.0 GHz). In the experiment the chimps showed slowdown in work function over a few days and then fell into deep sleep. Researchers later questioned the methods used during the experiment, but you can see where people might become very worried about microwave exposure, were they to read of this experiment.

On the other side of the athermal fence, one of the leading biophysicists (Schwan) assures us that since the resting potentials of nerve cells are in the kilovolt range and the induced E fields from microwaves are 10^5 times smaller, there is no mechanism for microwave effects on the nervous system.

Citizens and scientists alike will find the literature on the effects of microwaves quite bewildering. There are mountains of conflicting data, extrapolation from animal studies to humans is difficult to do and epidemiological studies of effects low levels of **anything** are very difficult to do with any meaning because there are so many variables. Physical scientists, biologists and physicians will need to team up and do more research in order to lay some of theses doubts to rest.

Effects of SPS microwaves on communications

The one item that the CDEP report had definite conclusion on was that SPS microwaves would cause interference to a) other satellites in GEO, b) satellites in LEO and c) ground based electronics and communications within 100 km of the rectenna. Interference can be avoided with proper shielding of other communications equipment, but studies of more depth than done in CDEP will have to be carried out.
Some of the CDEP findings:

* LANDSAT passing thru SPS beam would suffer increased video noise, control signal jitter, reduced dynamic range; any one of these would result in

degradation of LANDSAT pictures. (LANDSAT would be in the beam for about 13 seconds).

* Spacing in GEO from SPS to other satellites would have to be 1 degree or more

* SPS beam side lobes might cause interference to satellites in GEO across the ring.

* Most television and infrared sensor systems would not experience interference if located more than 50 km from the rectenna site. (Does this mean that I would have a fuzzy picture on the TV if I live with 50 km??)

* Computers would have to be located near the rectenna would have to have mesh shielding inside plastic cabinets. (At least for IBMs, they already have this).

The effects of launching

The CDEP report assumed it would take 375 heavy launch vehicle launches plus 30 personnel vehicle launches per year for 30 years to build and maintain 60 SPSs. I deduce that this means it would take 202.5 launches for one SPS. With the advent of SPS designs based on lunar materials, the number of launches from Earth for materials would be around 1% of this number. HOWEVER! If we intend to build a real infrastructure in space including space stations, lunar bases, SPS and space colonies, I can easily envision launching 400 times per year. According to the almanac, 56 million passengers flew in and out of Chicago's O'Hare airport last year. If we assume each plane holds about 300 people, that amounts to over 500 flights PER DAY! So I don't think we can shrug off the effects of launching. Keep in mind that the Soviets already launch 100 rockets per year. We must use our imaginations on foreseeing environmental problems as well as for foreseeing the opening of the High Frontier.

A recent article in Aerospace America gives some new numbers on pollution due to rockets[6]:

Annual contributions (in thousands of tons) of stratospheric Cl, H_2O, H_2 and NO_x

source	Chlorine	water	H_2	N
industrial	300			
volcanoes	100-1000			
natural	75	15,600	340	2
rockets	0.79	3.25	0.2	0

These exhaust products from today's rockets contribute to ozone depletion. From the table, the contributions to ozone depletion from rockets is small. Popular articles proclaiming that rocket launches are going to destroy the ozone layer are, for the moment, just uninformed sensationalism. Nevertheless, experts cannot sit back smugly and tell us that rockets will not be a problem. Later in the same article, the (rather smug) statement is made that "it would take an estimated thirty-fold increase in launch rates to increase global ozone depletion by 1%." This meant 30 fold from 9 shuttles and 6 titans to 30x(9+6) = 450 per year.

Space debris

These are just some of the issues associated with the environmental impact of SPS. See [2] for findings in the other areas of concern. Since CDEP, a new issue has come up also, that of space debris. Although the chance of a satellite in GEO being hit is only about 1 in 10^6, these satellites present small cross sections of perhaps a few square meters. Since an SPS will be around 10^6 square meters in size, we see immediately that the chance of it being hit by space debris is 100%! This means that while designing an SPS, we will also have to design garbage collectors to remove large items and perhaps special bumper systems to keep small bits from doing too much damage. No one is going to stand for dirtying up GEO, a valuable world resource.

What's to be done?

We cannot sweep these problems under the rug. Various risk/benefit analysis need to be done for SPS. For example, studies should be carried out on how to mitigate effects of rockets on the stratosphere. Studies should also be conducted to determine how much ozone depletion could be reduced by siting certain heavy industries in space, and by using SPS power rather than burning fossil fuels. It may turn out that the saving of ozone due to such siting would outweigh the depletion due to launching! One sided reports on either "how wonderful it is" or "how hazardous it is" tend to mislead the reader in one direction or the other.

Engineers, working to develop new power systems, frequently ignore the issues of environmental impact. They tend to focus on solving the technical problems of how to make an efficient system. Naturally, it is the engineering aspects that engineers find are most fun to work on. However, in today's social climate of 'not in my back yard' and real

environmental conciousness, it will be to the engineers' distinct advantage to address some of the environmental and safety issues of any new type of power generation system early in its development. All power generation systems have a list of advantages and disadvantages and risks/benefits. These will have to be rationally weighed, not only by engineers and scientists but also by the public at large. First, the designers and proponents of any system will have to understand the advantages/disadvantages and risks/benefits. To put it bluntly, the proponents of a system, such as SPS, must admit to themselves, that everything is not "sweetness and light". There are environmental impacts and hazards to human health to be considered. Second, they will have to summarize the advantages/disadvantages and risks/benefits in a format that can be understood by non-experts. Third, the public will have to be educated of these facts. This education phase is difficult and expensive. Engineers and other technical people often find this is tedious and it is time consuming. Due to the sad state of science education in the USA, the task of getting average citizens to understand even the simplest technical fact can be frustrating. But I firmly believe this will have to be done or SPS industry will fall into the same guagmire that nuclear power industry has.

It is interesting that hydroelectric power was generally accepted by the (US) public, in spite of the fact that more people have died from it (due to dam failures) than from any other power source. There are 2 obvious reasons for this acceptance. First, hydroelectric power stations were key to the industrialization of the USA. At the time of the first large stations in the northwest (in the 1930's), availability of power meant having the ability to run factories, thereby increasing the wealth of the region. People had jobs, made money and the standard of living improved. The other reason is that some of the power companies spent money on promoting the power stations to the public. They even went so far as to hire folk-singer Woodie Guthrie to write and sing songs about the Grand Coulee dam and the Columbia river. [What? Songs about SPS?? Imagine it!]

In contrast, nuclear power has generally been vaguely associated with bombs. People generally feel they cannot understand the workings of nuclear power plants and experts tend to back these feeling up.

The HBO hearings show just how difficult it is to get people to truly understand the technical literature and the expertise of experts. People tend to leave the technical stuff to the experts until it becomes a local issue...then they do not trust the experts.

It is not sufficient to simply tell people "trust me, I'm the expert...it's no problem". People will have to educated from the ground up. For example, microwave power densities should be put into perspective.

Power densities of gadgets with which we are familiar compared to SPS

regular radio
0.000005 milliwatts/cm^2

microwave ovens
inside: 700 to 1000 milliwatts/cm^2
outside: < 10 milliwatts/cm^2

airport radar
~ 0.005 milliwatts/cm^2

US maximum exposure standard
10 milliwatts/cm^2

SPS baseline maximum power
23 milliwatts/cm^2
at rectenna center

SPS exposure under rectenna
5 milliwatts/cm^2

SPS exposure at rectenna
0.1 edge milliwatts/cm^2

Reading through the literature, I have seen different units and even different measures. To the non-expert, this type of presentation of the information is totally incomprehensible! Even some alleged power experts have referred to the SPS beam as a death ray, revealing that they have no comprehension of the power levels involved. [5]

The final message I have for you is that if we EVER hope to build an SPS, we MUST devote significant time and money to

a) research into environmental and health problems from SPS leading to well written risk/benefit analyses and

b) education of the public and ways to include the public in decisions on new power generation systems from the very beginning.

If the issues of environmental impact and safety are not addressed with as much or more vigor than the technical ones, there will never be any chance of building an SPS, especially one for beaming power to Earth.

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A4.2 The Environmental benefits of Solar Power Satellites

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ABSTRACT

The environmental issues associated with satellite power systems can be placed into two categories. The first is the environmental impact that either the building or operating satellite power systems will have on the Earth's biosphere. The second, which appears on the credit side, is the degree to which the environmental impact of a technical civilization on the biosphere is lessen or attenuated by sub-stituting electric power from orbit for electric power from coal, oil and nuclear power plants. This paper is a discussion of the environmental credits which can be attributed to using electricity provided by solar power satellites.

RESUME

Les conséquences environnementales qui résulteraient du développement des systèmes de satellites à énergie solaire peuvent être classées en deux catégories. La première est l'impact environnemental qu'à la fois la construction et le fonctionnement de ces systèmes de satellites auront sur la biosphère terrestre. La seconde, qui apparait comme bénéfique, est le point auquel on parvient à atténuer ou à accentuer les effets d'une civilisation technique sur la biosphère en substituant l'énergie électrique émise depuis une orbite à l'énergie issue du charbon, du pétrole et des réacteurs nucléaires.

Cet article traite des avantages pour l'environnement qui peuvent être attribués à l'emploi d'énergie générée par les satellites à énergie solaire.

Introduction

To the Biblical list of the four great plagues of mankind the modern age has been able to add another scourge: environmental pollution. Pollution has become a global problem and the search for solutions an international quest. It is a quest with a moral challenge of creating an infra-structure for sustainable and equitable development. This quest and challenge presents the proponents of satellite power systems (SPS) with an unique opportunity. Can we, the proponents of this technology, justify energy from space as a component of sustainable development? If we can and also demonstrate that it is economical then we will have a program and a power satellite.

Using the resources of space to meet the dual challenges of energy and environment provides us with a way to appeal to the youth (of the world) who seek nourishment in dreams, as well as in bread (Pollock, 1980). The enthusiasm of our children is not enough. We also need the support of the taxpayers and the politicians. For the taxpayer we must establish the linkage between energy from space, the quality of the environment and his life. In order to the win the support of the politician for the SPS concept we must demonstrate it is relevant, cost effective and will make heros out of the politicians who support the concept of energy from space.

Emissions such, as carbon dioxide, sulphur dioxide and nitrogen oxide, from thermal power plants, coal, oil and LPG, contribute to long term and global environmental damage. While the issue of global warming is still being hotly debated there remains little doubt about how acid rain is created and what is it's effect on the biosphere. The most obvious solution is a reduction in the use of fossil fuels for power generation. But what then are our options?

Starr and Searl, 1990, stated in an Electric Power Research Institute study that although both nuclear and solar electric are capital intensive they both share the ability to be expanded without being natural resource limited. They go on to state the rather obvious fact that terrestrial solar is limited by its diurnal dependence and its need for a storage system if it is to break the chains of this limitation. In addition, they point out that competitive use of land and water for food production may be a major constraint on the use of biomass as a fuel as the world population grows. This ignores the already demonstrated problems of deforestation and desertification which is caused by the excessive use of biomass for fuel in the developing nations.

As a counterpoint to Starr and Searl's advocacy of nuclear power as an end all solution to global energy problems Markovic, 1990, points out that the impossibility of (finding a political and socially acceptable) solution to the problem of depositing nuclear wastes might be a single sufficient reason to give up nuclear energy altogether. But what then are our options?

I propose, in spite of the curious almost studied way that the satellite power solution is ignored by energy planners, that energy from space is a viable solution to the environmental problems posed by power generation. It is not an end all solution and given both the historical time constant of a half-century for substantial changes in the mix of large scale energy systems reported by Starr and Searl, 1991, and the need for testing and evaluation, it is not a threatening technological alternative to vested interests. Rather it is the dark horse or technological long shot. However to be an environmentally viable solution its impacts must be mild when compared to the alternatives and since SPS is the new kid on the block its benefits must be large.

Environmental Impact of Building SPS

There are at least two major environmental concerns about energy from space. They are the effect of the particulates ejected from the vehicles launching construction materials to LEO and the effect of microwaves on the atmosphere. The former is highly dependent upon the acceleration of the launch vehicle, transit times through atmospheric layers and the type of propellant used.

The first concern can be subdivided into three phases. The three phases are: technology validation and demonstration, establishment of the technology as a viable alternative and competitor to other forms of generation and as a mature source of environmentally benign energy.

Currently there is no foreseeable way to avoid impacting the environment during the first two phases. The questions to be answered here are: what is the magnitude of that impact and is the long term benefit to the environment worth the short term insult to the environment. A design constraint which should be considered for future launch systems is the type of propellant that will be used (injected) at different altitudes.

Table 1 lists the amounts of propellant that will injected into the atmosphere per 19,000 kgs of payload to LEO. As can be seen there is a great deal of improvement that can be made in reducing the amount of pollutants per pound of payload.

However in the third phase we can finesse the rocket plume pollution problem by deriving most of the necessary construction materials from the Moon and those we can't we might be able to use a mass driver located on the equator where the payload has a brilliant pebbles type rocket and control unit for placing it in orbit.

The microwave issue needs to be truly researched not paper studied into the ground. The public has valid concerns and the field of research is new enough that there is a lack of knowledge about the effects of different strengths of microwave energy at different frequencies. However, to develop the necessary data requires a test bed system for all up testing. Testing which can be done at all altitudes. Small scale experiments in a laboratory are necessary but we will not be able to address conclusively the public's concerns until we have a test bed which models the complete system.

If we do not address the environmental and health impacts of the technology of energy from space early in the program we will face the same problems that nuclear energy now faces. Morone and Woodhouse, 1989, present in *The Demise of Nuclear Energy? Lessons in the Democratic Control of Technology* an excellant set of lessons learn about how not to go about implementing a new technology.

Table 1 Metric Tons of Particulates of Propellant injected into the atmosphere per 19,000 kilograms of payload to LEO

	Titan IV	PROTON	Shuttle	Ariane 4	Long March
Payload	15,700.	20,000.	25,000.	4,200.	1,400.
ratio	1.21	0.95	0.76	4.52	13.57
Propellant Type	+ Solids	+ Solids	LOX/LH2 + Solids	+ Solids	
Propellant Mass (kg)	185,400.	603,000.	1,706,400.	418,000.	185,500.
Prop to Pay	(11.81:1)	(30.15:1)	(68.26:1)	(99.52:1)	(132.5:1)
Total Mass Propellant	224,334.	572,850.	1,296,864.	1,889,360.	2,517,235.

The Environment Benefit of SPS

Environmental consequences of economic policy decisions are complex and far-ranging. They typically involve conflicting interests. Air pollution produced by oil and coal combustion travel hundreds of miles to shower down as acid rain. Acidity can build for years with seemingly little harm - until, in a classic example of catastrophe theory, it finally exceeds the natural buffer capacity of the land and water and overnight forests, lakes and streams start to die. There are no choices which do not impact the environment. The question is which energy technology has less impact?

Environmental problems are also inseparable from the problems of development. Decision makers in developing countries faced with limited resources, high rates of population growth and the need for energy for development are often forced to compromise the environment.

Current options each comes with a cost. Dams often dislocated people, flood land and may create health hazards through water borne disease. Coal mining disrupts the environment and coal-fired power plants pollute the atmosphere and the land while heating rivers and lakes with the discharge from the plant's cooling system.

Tables 2 and 3 are a qualitative summary of cost elements, many of which are often externalized in pricing the cost of power, and environmental and safety risks for various forms of power generation. Table 4 is the beginning of a quantitative statement about the cost of emissions. A great deal more work needs to be done to complete this table in a through and unbiased manner. There are however some additional qualitative statements which can be made about the benefits of energy from space. The data on carbon emission was taken from Amagai, 1991 while the cost of six dollars per ton for carbon emissions was taken from a Wall Street Journal article.

SPS and the Industrialized Nations

The industrialized nations with 24% of the world's population, generates about 80% of the world's electricity (Starr and Searl, 1990). As a result they inject the most emissions into the biosphere. They also have the capital needed to finance megaprojects. It is obvious from both an environmental and financial point of view that they are the place where satellite power systems should be first introduced.

However, according to Starr and Searl, 1990, there is a historical time constant of a half-century for substantial changes in the mix of large scale energy systems. This is in keeping with both the planned life expectancy of generation facilities (30 years) and the rate of capital formation that takes place within a new industry. It also fits with the 17 year cycle required for new ideas to penetrate existing power structures and to start to have an effect on the younger decisionmakers moving into power positions. Consequently, if we look for the implementation of the SPS concept to change the way the industrialized nations effect the environment through power generation we will have a long wait.

On the other hand two factors, population growth and the desire to achieve the same levels of development as exist in the industrialized nations point to the developing nations as a major source of new atmospheric pollutants unless they are offered an alternative to fossil fuels. China alone is planning to build over 200 coal fired power plants over the next 30 years.

Benefits to Developing Countries

Making choices in the search for environmentally sound energy sources can be difficult. Countries need energy to develop, to provide alternatives to the destructive use of

Table 2 Environmental Cost Items for Determining the True Cost of Electrical Energy to Society

Phase of Operation	Coal	Oil	Gas	Nuclear	SPS
	Type of Base Load Generation				
Construction	Low environmental cost Cost of Const. (Len. of time)	Low environmental cost Cost of Const. (Len. of time)	Low environmental cost Cost of Const. (Len. of time)	Low environmental cost Cost of Const. (Len. of time)	Rocket Plume Cost of Const. (Len. of time)
Operation	Strip mining Air Pollution Water Poll. Thermal Poll. Sludge Disp.	Air Pollution Water Poll. Thermal Poll.	Air Pollution Thermal Poll.	Strip mining Thermal Poll. Spent Fuel	None
Decommision.	Land Restoration of strip mines Sludge Ponds	Little	Little	Land Restoration of Uran tailings Spent Fuel Rad Waste Decom. Ops	Little anticipated
Size of Plant	600 MW			1,000 MW	1,000 to 5,000 MW
Area Effected					
Notes	1				

Notes to Table 2

1. Some European countries have already started applying a tax to emissions from coal-fired power plants. In one case the tax is 6 dollars per ton of pollutants. There is also discussion underway of taxing carbon and sulfur emissions at different rates.

Table 3 Environmental and Safety Risk and Hazard Assessment of Generation Methods

Phase of Operation	Coal	Oil	Gas	Nuclear	SPS
	Type of Base Load Generation				
Construction	Normal Construction Hazards	Normal Construction Hazards	Normal Construction Hazards	Normal Construction Hazards	Launch Ops EVA's
Operation	Normal Plant Operations Lung Cancer (coal mining) Mining Accidents Acid Rain	Normal Plant Operations	Normal Plant Operations	Normal Plant Operations Loss of Coolant	Undetermined effects of microwave radiation
Decommision.	TBD	TBD	TBD	TBD	TBD

biomass for fuel and to improve the quality of life for their people. The struggle to survive has led people to ask to much of their forests. In developing countries seven out of ten people depend on fuelwood to meet their heating and cooking needs. Villagers cut trees if they do not have access to cheap alternative fuels. As supplies of fuelwood dwindle, people stop using dung and crop cuttings for fertilizer and begin using them for fuel. Once this happens the land very quickly loses its fertility. Crop yields drop, the land dries out and erosion sets in.

Example: In Mozambique, the burning of fuelwood accounts for 80 percent of all household energy (World Bank, 1989). The demand has led to deforestation and air pollution. As a result a project has been initiated by the World Bank to develop other sources of energy and connect more houses to the electric power system. The project also includes a program to market new home cooking devices. Unfortunately energy from space under an energy as foreign aid program was not considered.

Table 4 Quantfication of the Externalized Cost of Environmental Pollution from various types of Generation

Emission or Waste	Quantities Costs	Type of Base Load Generation: Coal	Oil	Gas	Nuclear	SPS
SO_2	Metric Tons					
	Tax ($/ton)				N/A	N/A
	Cost/kw-hr					
NO_x	Metric Tons					
	Tax ($/ton)				N/A	N/A
	Cost/kw-hr					
CO_2	Metric Tons	10,378,520	25,033,450	22,961,030		
	Tax ($/ton)	6	6	6	N/A	N/A
	Cost/kw-hr	0.099 cents	0.099 cents	0.099 cents		
Spent	Metric Tons					
Fuel	Tax ($/ton)	N/A	N/A	N/A		N/A
	Cost/kw-hr					
Rad Waste	Metric Tons					
Disposal	Tax ($/ton)	N/A	N/A	N/A		N/A
	Cost/kw-hr					
Rocket	Metric Tons					
Plume	Tax ($/ton)	N/A	N/A	N/A	N/A	
	Cost/kw-hr					
Total Externalized Environmental Costs						

Example: In Haiti the people are striping their land for fuelwood with the result that the top soil is then washed into the sea. They are losing their land as well as their forests, a consequence of the excessive use of biomass as an alternative fuel. But given the poverty and lack of other energy resources what choice do they have? While terrestrial photovoltaic systems could provide some of the power they need it cannot meet the total energy needs of a village without some sort of storage system. A storage system which according to Starr and Searl, 1990, increases the size of a system by a factor of 5

We can see that "perhaps the single greatest contribution that could be made to environmental conservation would be the invention of a satisfactory fuel-wood substitute" (Dregne, 1985). Energy from Space can provide an economical and socially acceptable substitute for fuel-wood. It would allow many nations to imple-ment development policies without the same degree of impact on the environ-ment that the industrialized nations have had.

Example: Another example of how satellite power can be linked to both environmental issues and economic development is the Carajas iron ore project in Brazil (World Bank, 1989). The desire to promote pig iron smelting demanded large quantities of charcoal which would be derived from natural forests. The World Bank is now helping with an energy options study, which unfortunately does not include electric power from space. . With Satellite Power as a development option there would be plenty of power for smelting, elimination of both the cutting of forests and the associated air pollution from making charcoal and burning it to make pig iron.

In Starr and Searl's study of Global Energy and Electricity Futures they show, p. 77, that without an alternative to fossil fuels the Lesser Developed Countries will increase their levels of emissions by 370% over the 1986 baseline. But how can we justify introducing energy from space to a capital poor region of the world?

An Environmental Rationale for SPS

Developmental Ethics

As we prepare to enter the 21st century we face the challenge of creating a paradigm for sustainable development which is ecologically sound and economically just over a multitude of cultures and generations. This moral challenge of creating an infrastructure for sustainable and equitable development presents the proponents of energy from space with an unique opportunity. An oppor-tunity

which was ignored or unreal-ized in the previous study age of the SPS.

Solutions, as well as the decisions about which solution to choose, have four components: technical, econom-ical, political and strategic. On a national level, the latter two components include the philosophy or gestalt of the nation or ruling political party. For any project, large or small, to succeed, it must address to a greater or lesser extent these four components as well as have its champions. Champions or politicians who sees that their support of this concept will make them heros to the people.

The political component, especially for major initiatives, has a strong social or moral aspect to it. Leaders of movements for social transformation, have always understood that in order to change a situation one must appeal, sooner or later, explicitly or implicitly, to moral as well as material consid-erations. With space, energy and the environment coupled to sustainable development we are dealing with social transformation. We have a solution to a global problem, we have a moral justification and if we look beyond our Earth to the Moon for the resources to build the power systems we have a frontier to excite the imagination of young and old alike.

Can we in good conscious deny the developing countries their place in sun on the basis that their need for energy for development will adversely impact the environment. The crafting of a solution to the global problems of energy, for development and subsis-tance, and the environment that is equitable across both societies and generations will require innovative, technically competent people. Technologists, managers and politicians who are capable of critical and constructive moral thought. technical solutions .

The justification for initiating the development and demonstration of energy from space will come, not from the short sighted financial projections of MBA's, but rather from the deeply embedded moral imperative of the human race to sow for the future rather than always reap for today. It will come from the compassion of the people of the industrialized nations for the poor and starving of the developing nations. The price for the R&D necessary will be paid in order to save the environment, to save the Alaskan Wilderness from the driller's bit and the rain forests from the peasant's axe. If the price is not paid soon we may miss the opportunity of deciding to control our future and be pushed into a downward spiral by forces beyond our dwindling resources to withstand. Developmental ethics will play a role in clarifying the values at stake in policy decisions and giving moral reasons for alternative courses of action (Engel, 1990)

Moral Questions, Moral Justifications

One of the many moral questions which technologists must face in creating solutions is: which solution provides the greatest opportunity for enabling sustainable development and economic justice (Engel, 1990) with the least environmental impact. Markovic, 1990, poses some rather rhetorical moral questions which if answered with energy from space as foreign aid proves a moral justification along with the environmental justification for satellite power systems. The ones I agree with and which support my thesis are:

- Is it moral for a few generations to consume the resources which are indispensable for the survival of all future generations?
- Is it permissible to irreversibly pollute the biosphere?
- What legacy will we leave our children?

Conclusions

Satellite Power Systems (SPS) can have a beneficial impact on the global problems of environmental pollution, the demand for energy and the economic imperative for development by the poor of the world. However for the SPS concept to have an impact and to attract the support needed to turn technological dreams into economic reality there must be more to the program than demonstrating another neat technological trick. The source of support lies within the realm of developmental ethics (Engel, 1990 and Goulet, 1990).

The future consequences of present actions and decisions have never before been as morally relevant and urgent as they are today (Kothari, 1990). As the linked and growing crises of energy, the environment and equitable development are showing us decisions taken at one point in time have a powerful impact on people and cultures which have had no voice and been given little consideration in the decision process. Decisions made today will affect future generations in ways which will be largely irreversible. With SPS we have a chance to colonize the future with hope and opportunity. A chance to provide environmentally benign energy while opening a path to the stars.

President Bush summarized the thrust of this paper in his greeting to the 1989 Global Change Conference where he said: "Let us remember as we chase our dreams into the stars that our first responsibility is to our Earth, to our children, to ourselves. Yes, let us pursue those dreams, but let us also preserve the fragile world we inhabit." Energy from space using lunar resources and provided to the developing nations under a program of energy as foreign aid will allow us to move outward to the stars while improving our biospheres and creating the possibility of sustainable development with economic justice.

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Related Work

This paper is one of four presented at the SPS 91 Conference. Their relationship is described below. Together they describe a vision for the future and a reasonable path which may be taken to transform that vision into reality

SPS-91.60, The Environmental Benefits of Solar Power Satellites, this paper, establishes an ethical and environ-mental rationale for utilizing the resources of Geater Earth to provide energy from space.

SPS-91.59, A Different Race: Global Rural Electrification Market Niches and the Third World as a Starting Place, describes a program for evolving the power satellites from small systems which we know how to do now to larger systems which we will know how to when the time comes. This paper extends the environmental rationale established in PS-91.60 to the economic domain and presents the concepts of energy as foreign aid and energy from space as a strategic alternative to the arms race.

SPS-91.58, Economic Impact of Using Lunar Resources to Build SPS Systems, assumes that the demon-stration project, SPS-91-61, has been sucessull and that systems have been scaled up to meet the needs described in SPS-91.59. It also builds on the environmental concerns described in SPS-91.60 and leads one in a ogical fashion to the cost effectiveness of using lunar materials.

SPS-91.61, The IGRE's 100 Kilowatt Demonstration Project, describes severl low cost demonstration projects which will provide proof of principle demonstration, a technology test bed, and be the first steps in series o gradually increasing larger satellites. The project is design to be accomplished within 4 years for less than 250 million dollars. A secondary purpose is to excite the public and an stimulate in youth an interest in science and engineering.

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A4.3 Satellite Power System (SPS) space debris management strategies and technologies

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ABSTRACT

This paper presents a contemporary systems approach to help evaluate the space debris environment uncertainties associated with the development, construction, operation, and eventual retirement of large satellite power systems (SPS). To assist in this process, the results of one contemporary space debris model are presented - enabling SPS planners to evaluate and project the potential consequences of their activities on the space debris environment and conversely the potential impact of an evolving (and growing) space debris environment on their construction and operational options. Space debris remediation methods, including active debris removal technologies, are also suggested as a complement to SPS development strategies.

RÉSUMÉ

Ce document présente une approche contemporaine de systèmes qui permet de faciliter l'évaluation des incertitudes d'un environnement de débris spatiaux, associées au développement, à la construction, à l'opération et à l'abandon éventuel des grands systèmes de satellite de puissance (SPS). Afin d'illustrer ce processus, les résultats d'un modèle contemporain de débris spatiaux sont presentés, permettant ainsi aux responsables du SPS d'évaluer et de prévoir les conséquences éventuelles de leurs activités sur l'environnement de débris spatiaux, tout en tenant compte de l'impact de l'environnement, déjà en cours de développement, sur leurs options de construction et d'opération. Les méthodes de réparation des débris spatiaux, y compris les technologies d'éradication sont proposées s'ajoutant aux stratégies de développement des SPS.

I. Introduction

The satellite power system (SPS) has the potential of supporting a sustainable global energy economy [1-3]. However, the vast majority of the SPS concepts proposed to date involve the on-orbit construction and operation of very largescale space systems whose dimensions, mass and overall space environment impact characteristics are essentially unprecedented in all previous space operations experience.

For example, Figure 1 shows the possible satellite configuration for a Reference SPS system that was sized for 5 gigawatts DC power output into a conventional terrestrial power grid [2]. This particular reference SPS satellite has one end-mounted antenna which transmits energy (in the radiofrequency portion of the spectrum) to a rectenna on the ground. The satellite configuration illustrated consists of a planar solar array structure built from a graphite composite material. Two different

photovoltaic conversion options are depicted in Figure 1. The first involves the use of single-crystal gallium-aluminum-arsenide (GaAlAs) solar cells with a concentration ratio of 2. The second solar energy conversion option involves the use of single-crystal silicon (Si) solar cells with no concentration. The GaAlAs option results in a five-trough satellite configuration with a solar blanket area of 26.52 km^2, a reflector area of 53.04 km^2, and an overall platform area of 55.13 km^2. The silicon cell option has a solar blanket with no concentrator, resulting in a blanket area of 52.34 km^2 and an overall platform area of 54.08 km^2. For either solar conversion option, the end-mounted microwave antenna is a one-kilometer diameter phased array transmitter.

Recent space debris reports by agencies of the United States government and the European Space Agency (ESA) have described the growing dimensions of the orbital debris population and the implications of this expanding population for all future operations in space [4-6]. These foundational reports and numerous other contemporary assessments of the space debris environment [7-9] are now implying that "left unchecked, the growth of debris could substantially threaten the safe and reliable operation of manned and unmanned spacecraft in the next century". [4-9]

While the present space debris population may pose little immediate constraint on either manned or unmanned space operations, because of the compounding effect of inevitable collisions between space debris (including the construction site debris that would accompany SPS on-orbit fabrication and assembly operations) and largescale space objects, there is a genuine concern that the risk of impact with orbital debris could represent a significant and growing threat to the development and operation of large space systems. Because collisions between large space objects and space debris can generate further debris, there is also a distinct possibility that a critical density of space debris might occur which then leads to a self-sustained debris chain reaction in orbital regimes needed for successful SPS fabrication, operation and maintenance.

Therefore, the unique and fundamental advantages provided by the SPS concept for a sustainable global energy economy in the 21st Century should not be constrained by a contemporary failure to adequately assess and circumvent or mitigate the space debris issue as it might relate to the SPS. The satellite power system will not only be affected by the 21st Century space debris environment, it also represents a major potential source of space debris throughout its lifetime: from on-orbit fabrication and assembly activities, to orbital power generation operations, to decommissioning and retirement. For example, it is not too early to ask: What does one do with a multi-kilometer sized space object in geostationary orbit at the end of its operational lifetime (typically 30 to 50 years)? Few SPS advocates have concerned themselves with post-operational decommissioning issues for satellite power system complexes, whether these systems are retired at the end of a normal mission lifetime or are forced to prematurely cease operation because of a catastrophic accident or malfunction.

II. Space Construction Activities

Many of the space systems planned for the future are so large, massive and complex that placement in orbit can only be accomplished by construction in space. A major objective of any Satellite Power System program, therefore, will be to develop and implement the capability to perform space construction operations in low Earth orbit (LEO), geostationary Earth orbit (GEO) or other required extraterrestrial work sites.

Figure 2 depicts a generic space construction facility in low Earth orbit that could be used to develop and demonstrate an initial (litter-free) systems-level space construction capability, including installation of subsystems [10]. One major functional requirement of this space construction facility should be to support the engineering and development of space construction equipment and assembly procedures that minimize the production of space debris. These activities include: fabrication of members from raw stock; erection of structures from prefabricated components; deployment of preassembled, folded members; and assembly of these members with subsystem components to make up complete space systems. Typical space construction equipment will include holding and alignment fixtures, beam builders, manipulators, end effectors and remote work stations.

Another major SPS system construction requirement will be the ability to construct test systems for design verification (prior to fullscale system development). For example, Figure 3 shows an SPS Test Article system being fabricated in low Earth orbit prior to transfer (via electric propulsion systems) to geostationary orbit. This particular SPS Test Article would be a complete, independent spacecraft approximately 200 meters long. Its construction would involve fabrication of triangular beams; the connection of these beams to make a platform; installation of solar arrays, electrical conductors, and other subsystems; erection, installation, alignment and test of the microwave antenna; and installation of electric propulsion modules for orbital transfer. Throughout these construction and

assembly activities, procedures and equipment should be evaluated with respect to their suitability to support fullscale SPS development AND on the basis of their ability to minimize space debris generation.

III. Space Debris Environment

At the end of 1990, about 6,500 manmade objects were in orbit around the Earth [6]. Weighing in total about two million kilograms, these orbiting artificial objects are tracked and cataloged by the Space Surveillance Network (SSN) of the U.S. Space Command (USSPACECOM), which publishes an official object catalog each month [6,9]. Since the beginning of the Space Age on 4 October 1957 (with the launch of Sputnik I), a cumulative total of over 20,000 objects have been cataloged - of which approximately 14,000 have reentered the Earth's atmosphere and burned up. These cataloged space objects, some weighing up to several tons, reenter the Earth's atmosphere at a rate of two to three per day [6]. It should also be noted, however, that such space object data are incomplete, since the current Space Surveillance Network catalog includes only orbiting objects which are 10 cm or larger and which can be identified as to their origin [9]. Space scientists now believe that there are many more smaller objects (e.g., in the 1 to 10 cm size range - resulting from breakups of larger satellites) that are not currently represented in this catalog.

Furthermore, only 6 percent of the presently cataloged objects in Earth orbit are functional satellites - the rest of these orbiting objects fall into the category of space debris [6]. (See Figures 4 and 5) [6] Figure 6 presents a composite of the latest space object flux data (natural and manmade). The meteoroid population data are based on a wide variety of measurements made over past three decade, while the manmade object data are based on the space object catalog maintained by US Space Command (USSPACECOM) and an accumulation of contemporary space debris measurement data, including the latest measurements provided by experiments on NASA's Long Duration Exposure Facility (LDEF) [7,9,11].

Orbital debris is a growing problem. If current growth trends in the space debris population continue, by the year 2000 or 2010, some extensively used regimes in low-Earth-orbit could be rendered "too risky" for further use. Other orbits, including the strategically and economically important geostationary orbit (GEO) band, are also vulnerable to the growing space debris problem [4-6].

Even in the absence of a Satellite Power System program, the geostationary band contains a fast-growing spacecraft population which is now estimated at almost 400 trackable objects, including approximately 100 active satellites [6]. However, the exact number of manmade objects in GEO is not precisely known, because objects smaller than about one meter are currently untrackable at that distance from the Earth. (Some analysts speculate that there may be some 2,000 nontrackable objects now in GEO [6].) GEO represents a special space environmental regime, since objects placed there will essentially remain there forever, if not intentionally removed. Thus, while space experts estimate that the current space debris hazard at GEO is less than the "natural" space object collision hazard due to meteoroids, they are also quick to caution that improper (i.e., debris intensive) expanded activities at GEO could greatly increase the probability of destructive collisions. To permit full and productive international use of the GEO space regime (including future development of the Satellite Power System), additional experimental and analytical work is needed now to define the growing space debris hazard at GEO and to prevent this hazard from increasing exponentially with any anticipated future use of this very important orbital regime.

IV. Space Debris Modeling

A space debris model has been developed to predict the future space debris hazard to spacecraft [8,12]. The overall organization of this model is illustated in Figure 7. The sources of space debris considered are launches and their associated operational debris, explosion fragmentation debris, and collision fragmentation debris. The contributions of explosions and collisions are in terms of numbers of objects in various size regimes and do not contribute to the total mass on orbit. For space debris in low Earth orbit, the natural sink considered is atmospheric drag. Active space debris removal operations for end-of-life removal are also considered [8,12].

The overall approach of this fundamental space debris model is to assume that the debris density is uniform within 50-kilometer thick spherical shells. This is a reasonable assumption for space debris below about 2,000 km altitude. There is stronger latitudinal dependence for debris above this altitude. However, the higher altitudes are not used in averaging and provide an upper boundary through which some debris can be transported by fragmentations near 2,000 km altitude. These fragmentations would be rare events, since the density there is substantially reduced as compared to the debris density at 1,000 km altitude.

Generally, launches and operational debris are modeled as constant sources, or with percentage yearly increases. The size of the operational debris can be

varied as well as the number of pieces in each size group snd their deposition altitudes. The payloads are deposited among the altitude bins in proportion to the initial debris density distribution. This fundamental debris model was then used to produce a first order investigation of the consequences of a Satellite Power System development on the space debris environment.

V. Impact of SPS Construction and Deployment on Space Debris Environment

In order to assess the potential impact of the construction and deployment of a reference design Satellite Power System configuration on the space debris environment, a series of calculations were performed using the space debris model briefly described in Section IV and extensively discussed in reference 12.

For the purpose of this evaluation, the following assumptions were made regarding the reference SPS configuration:
(1) each operational SPS platform had a mass of 37.5 x 10^6 kg;
(2) fabrication and assembly of SPS segments was accomplished at a space construction center in LEO;
(3) deployment of the initial (prototype) SPS platform occurred in the year 2010;
(4) deployment of an additional 10 SPS platforms occurred between 2020 and 2030;
(5) a transit time of one year was required for SPS segments to be delivered from LEO to GEO;
and
(6) transportation of the SPS platform components from LEO to GEO occurred for platform segments ranging from 1/10th the total SPS platform mass (i.e., 3.75 x 10^6 kg) to 1/100,000th the platform mass (i.e., 375 kg).

It was also assumed that other space launch activities increased from the present baseline of approximately 120 launches per year by a rate of 5 percent per year over the next 20 years and then remained constant for the period of this analysis.

Figure 8 shows the estimated total number of debris objects in the size range of 1-10 cm projected over the next 120 years for a deployment of the reference SPS constellation from LEO to GEO in 375 kg segment sizes (a clearly non-economic, but technically interesting scenario). The number of debris fragments in this size regime is an indication of the debris hazard capable of causing catastrophic damage to other spacecraft and space platforms should a collision occur. Smaller-sized debris (i.e., < 1 cm) is also of concern for manned systems (including EVA activities) and because of possible damage to sensitive optical coatings and thermal control surfaces. However, this smaller-sized debris regime was not included in the present analysis, since the principal objective here was to perform a first-order investigation of the effect of deploying a major space system, such as the SPS, on that portion of the space debris environment capable of propagating further catastrophic damage.

The results of our analysis show that the number of space debris objects in the 1-10 cm size range would be expected to increase by over two orders of magnitude over the next century and that the deployment of the reference SPS configuration would increase the overall debris environment by approximately a factor of three.

The debris model results depicted in Figure 8 assume that cooperative international efforts are successful in eliminating intentional or accidental explosive destruction of expended or derelict space systems, that relatively simple debris remediation methods have been implemented to support end-of-life removal of expended satellites from orbits with altitudes less than 400 km, but that no systematic approach was being taken for the end-of-life disposal or removal of expended space systems and derelict space objects above 400 km altitude.

Since the growing debris environment is already of concern for important space systems planned for deployment over the next 20 years (e.g., Space Station Freedom), it is distinctly possible that efforts will be undertaken to develop a technical and economical means of removing all space systems at the end of their useful mission lifetime. Therefore, we also considered the effect that deployment of the reference SPS configuration would have on the space debris environment, if a companion space debris removal system was also developed and was capable of removing both satellites at the end-of-life and approximately 100 large (i.e. > 10 cm) derelict space objects per year from the existing space debris inventory. The results for this particular analysis are provided in Figure 9. While a significant reduction in the growth of the overall space debris environment can be anticipated in this scenario, it is also indicated that the debris environment impact of the reference SPS system is now relatively more important. It should also be noted that space debris generation resulting from deployment of the reference SPS configuration is the result of energetic collisions with the existing debris environment. It is likely that some functional damage would result from these collisions.

Since the collision frequency between space debris objects is proportional to the square of the number of debris objects in orbit, it was anticipated that the SPS system segment size that would be transported from LEO to GEO for final assembly and operation might have an

effect on debris generation. Figures 10 and 11 show the effect (based on a statistical collision frequency model) of SPS component segment size during the deployment of the reference SPS configuration. It is interesting to note that debris generation from deployment of the reference SPS system can be effectively avoided (according to the analytical model), if segments of the SPS system are transported from LEO to GEO in segment sizes of 3,750,000 kg or larger. (The solid curve in Figures 10 and 11 corresponding to 3,750,000 kg segments closely approximates the "No SPS" curve appearing in Figures 8 and 9).

VI. Conclusions

Based on the analysis of debris generation resulting from the deployment of the reference SPS configuration examined in this study, the following findings are offered:
(1) an effective debris removal system appears to be a necessary companion to the development and deployment of a Satellite Power System;
(2) protection of SPS segments from the existing debris environment should be considered during transport from LEO to GEO (if such an SPS development and deployment strategy is followed);
and
(3) debris generation appears to be minimized by transporting larger (versus smaller) mass segments of an SPS system from LEO to GEO.

Several general conclusions and observations also resulted from this study.

First, in developing a construction and deployment strategy for any Satellite Power System concept special attention needs to be given to the space debris environment. Specifically SPS planners must ask: How will the proposed system deployment be effected by the then existing debris environment? SPS planners must also ask: How will the SPS system (during and after deployment) effect and influence the debris environment?

Second, SPS construction and deployment activities should adopt from the very beginning of the program as many "litter-free" procedures and processes as possible. Early SPS engineering testbeds in low Earth orbit facilities should be used to design, develop and validate construction and deployment techniques which contribute the least possible mass and number of "derelict" objects to the growing space debris problem.

Third, a more thorough analytical and experimental understanding of the space debris environment at GEO is needed.

And finally, it is definitely not too early to consider and start planning for end-of-life disposal or decommissioning of SPS platforms. Should these giant platforms be continuously maintained and refurbished with operational lifetimes extending for centuries? If not, should they be designed for "mothballing" on orbit, for decommissioned disposal at a higher Earth orbit, or perhaps for dismantling and material recycling (at an orbiting space environmental protection center)?

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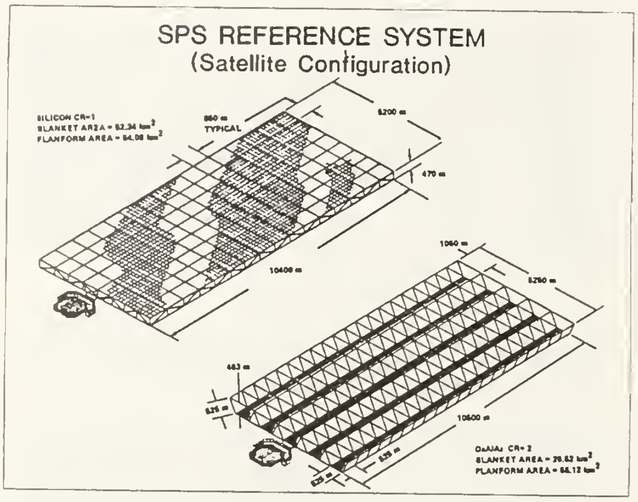
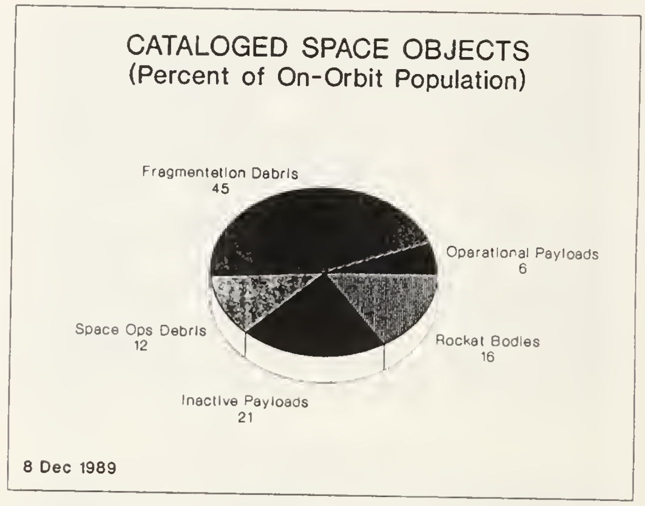


Figure 1



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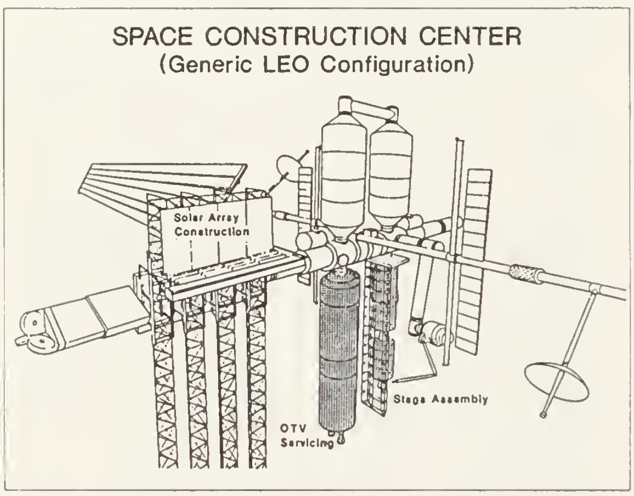


Figure 2

SPACE DEBRIS
(Typical Components)

- Spent Rocket Stages
- Inactive/Deactivated Spacecraft
- Rocket/Spacecraft Fragments
- Solid Rocket Motor Exhaust Particles
- Paint Flakes
- Spacecraft/Rocket Separation Hardware
- Spacecraft Coverings/Thermal Insulation
- Spent Nuclear Reactors (primarily Soviet)
- "Lost" Tools (from EVA activities)

Figure 5

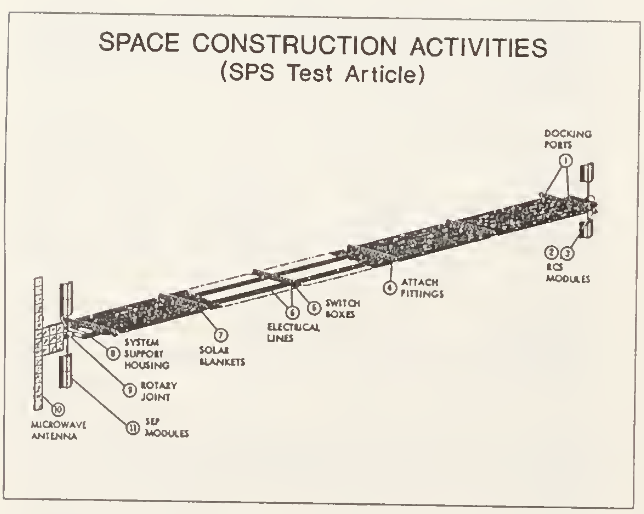
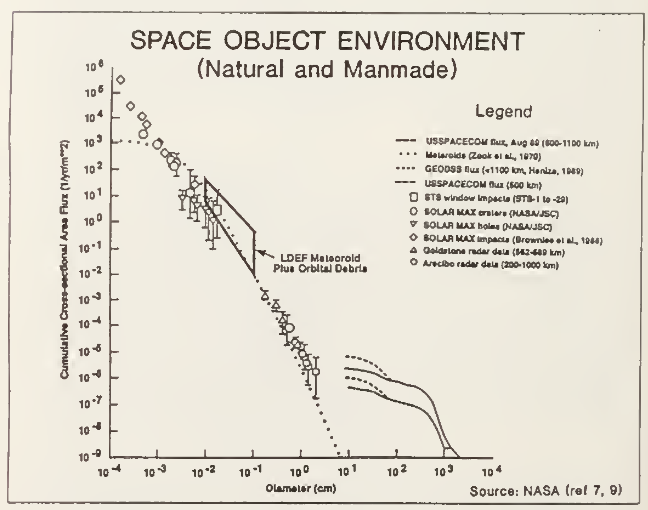


Figure 3



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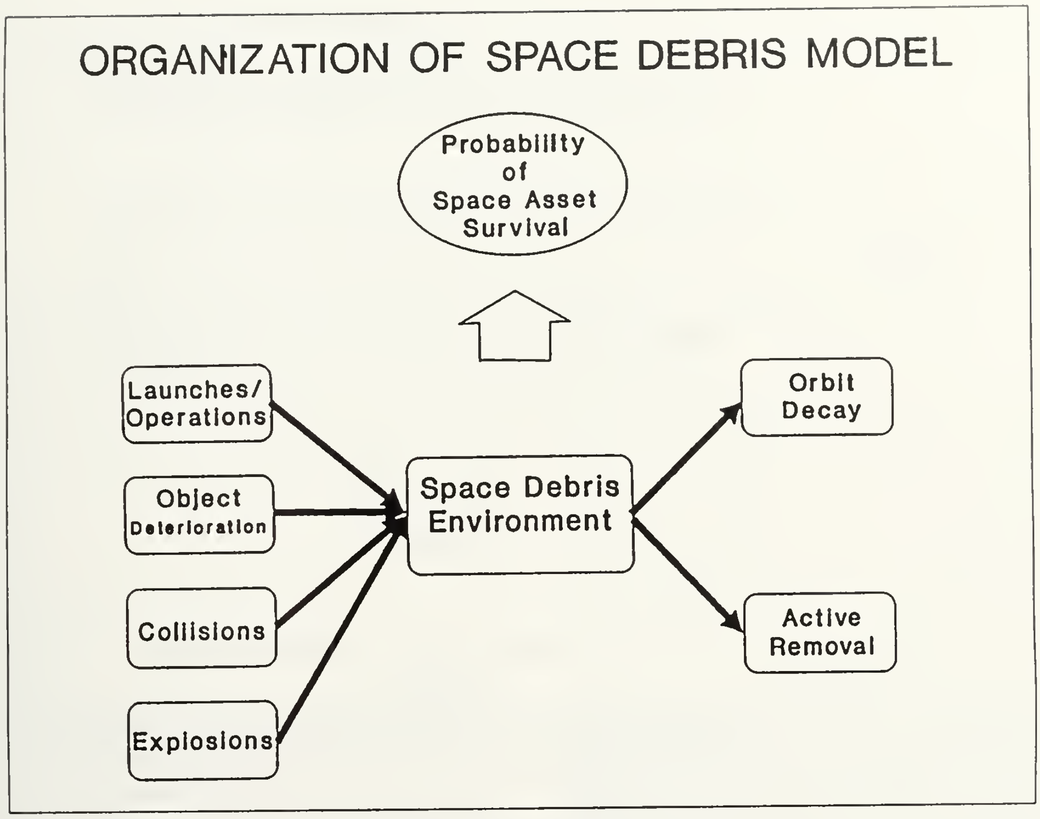

Figure 7

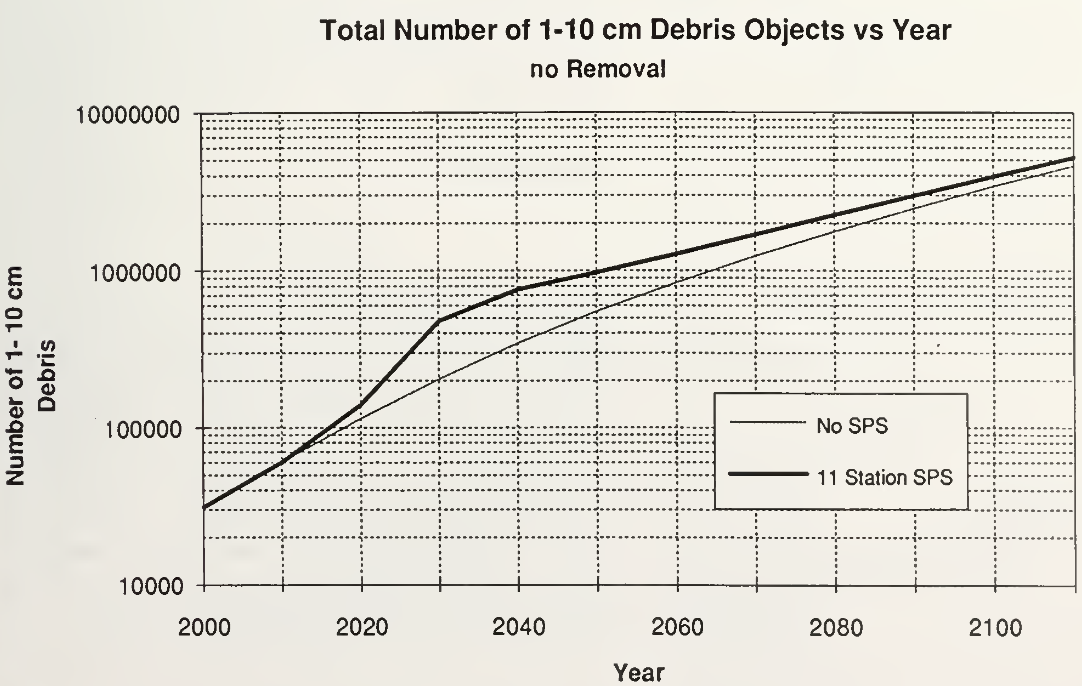

Figure 8

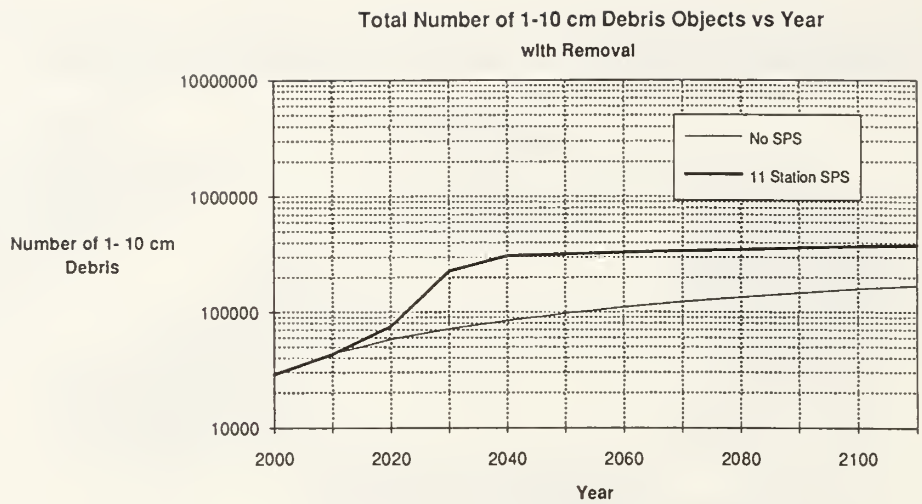

Figure 9

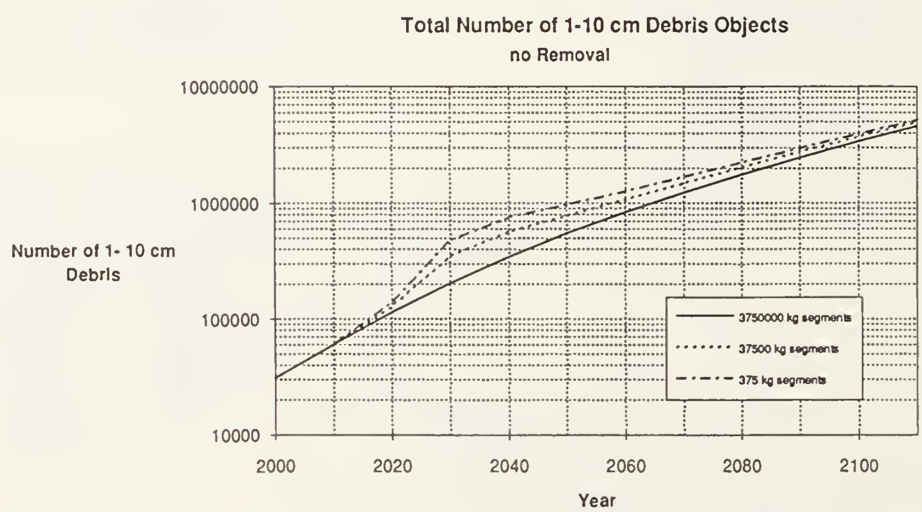

Figure 10

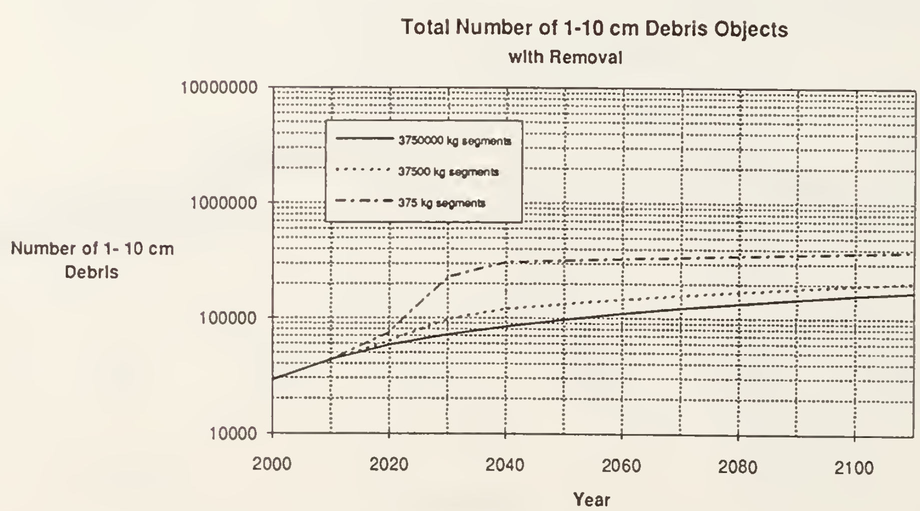

Figure 11

A5.1 The impact of technology advances upon Satellite Power Systems

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ABSTRACT

Previous studies of satellite power systems, carried out in the 1960's and 1970's, usually had the major disadvantage of large orbital mass, and hence a high level of launch support requirement. However, since that time the state of technology in many areas has advanced considerably. It is reasonable to assume that the satellite power system designs, if undertaken now, would exploit these advances. An example of a power system using lasers for energy transmission is used to illustrate the impact of such technology advances.

RESUME

De précédentes études de systèmes de production d'énergie placés sur satellites faites dans les années 60 et 70 avaient habituellement le grand désavantage de nécessiter des masses élevées en orbite, et par là de recourir à des capacités de lancement importantes. Cependant, depuis lors, le niveau de la technologie a considérablement évolué et ceci dans de nombreux domaines. Il est raisonnable d'affirmer que la conception actuelle de tels systèmes exploiterait ces progrès technologiques. Un exemple de système de production d'énergie utilisant la transmission par faisceau laser est utilisé pour illustrer l'impact de tels progrès.

Introduction

One of the major disadvantages with high power (> 100 MW) satellite power system (SPS) designs evolved in the 1960's and 1970's was the large orbital masses, and the launch support required as a result of these.

Table 1 gives a mass breakdown for a Lockheed design of a 500 MW system[1]. This system was based in low Earth orbit and used a CO_2 electric discharge laser for power transmission.

The concentration of mass in the energy exchanger/binary cycle, power generator and conditioner, and in the laser itself, is notable. Efforts to reduce these masses should have a large impact upon total power satellite mass.

Table 1 Lockheed Laser SPS Mass Breakdown

Component	Mass (t)
Collector	243
Solar Cavity	518
Energy Exchanger/Binary Cycle	1326
Power Gen. and Conditioner	718
Laser	1809
Structure	94
Telescope(2)	90
Others	148
Total Receiver/Transmitter in LEO	4946

This paper examines the effect of technology advances upon satellite power system design. Particular areas identified for discussions are those relating to materials advances, the influence of new materials upon the cycle thermodynamics, the laser type and efficiency, solar reflectors and collectors, and adaptive optics.

Materials Advances

Many new materials have been developed over the past few decades, particularly for aerospace applications. It is not possible at this stage to predict the likely mass reduction with new materials, as this would require a further detailed investigation into the various SPS designs. However, it is of value to review the relevant new materials and their aerospace applications as a guide to the likely impact on the power satellites.

Among the important material properties for the high mass components of Table 1 are strength, stiffness, temperature capacity and density. All these characteristics can be improved with materials developed since 1980. The main materials of interest here can be categorised as

a) Metal matrix composites (MMC),
b) Ceramic matrix composites (CMC),
c) Carbon - carbon composites (C-C).

An indication of the predicted usage of these materials in jet engines is shown in Figure 1[2]. The trend to replace traditional materials in jet engines (and in aerospace applications generally) is driven principally by the potential saving in mass, since this is a premium factor in aircraft, as well as in spacecraft.

Metal matrix composites (MMC)

Reviews of the development of MMCs are given by Bashford[3] and Trumper[4]. MMCs are a broad class of materials in which a metal matrix is reinforced with either particles, wiskers or fibres. For aerospace applications the matrix is commonly aluminium, nickel or titanium; and boron, silicon carbide, carbon and alumina are typical reinforcement materials.

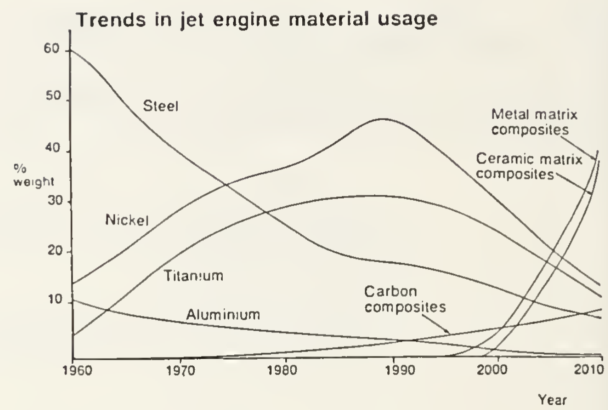

Figure 1 Predicted trends in jet engine materials usage

MMCs are superior to "conventional" composites eg. glass reinforced plastics (GRP), in that the use of a metal matrix gives a higher strength and a higher temperature capacity. An indication of the useful temperature ranges of MMCs and other materials is illustrated by the specific strengths (ie. strength divided by density) shown in Figure 2[5].

Examples of aerospace applications of MMCs are the cargo bay section of the Space Shuttle, where the load bearing skeleton is made from boron fibre reinforced aluminium tubular struts[4], and aero-engine fan blades in a similar material[5].

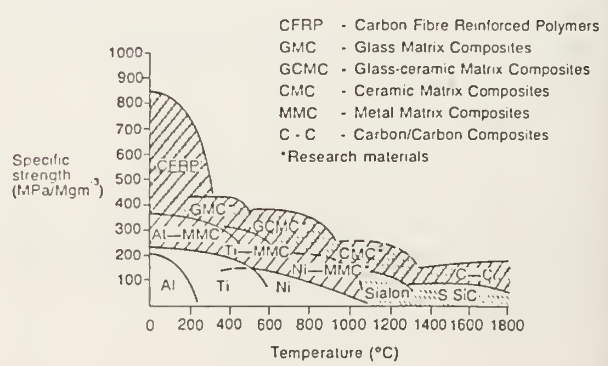

Figure 2 Specific strength as a function of temperature for various materials

As with other composite materials there is a wide range of permutations of reinforcing material, matrix material and composite configuration. Hence for full optimisation advanced composite material components require the component and the material to be designed together.

Ceramic matrix composites (CMC)

Conventional monolithic ceramics are noted in respect of their stability and stiffness particularly at high temperature, but have low toughness. This low toughness can cause the propagation of defects as cracks right through components. By separating the monolithic structure into fibre reinforced and a modestly bonded matrix so-called "psuedo-ductile" ceramics can be made[3]. This description is slightly misleading however since the components can still be brittle, but crack propagation is inhibited by the dual structure, thus preventing catastrophic failure in components. Typical CMCs are carbon, alumina or silicon carbide fibres in a silicon carbide matrix.

The high temperature capacity of CMCs makes them ideal for certain space applications such as (a) external and thermal protection (b) substructures and airframes (c) fuel containment and (d) propulsion and engine systems[3]. Near term applications include turbine blades for aero-engines[5].

Carbon-carbon composites (C-C)

A review of carbon-carbon composites is given by Savage[6]. They consist of carbon fibres embedded in a carbonaceous matrix. Carbon fibres have been used for many years as a reinforcement for polymer matrices. Replacing the polymer with carbon greatly increases the strength and useful temperature range. Although both components are the same element they are of different allotropic forms:- typically a highly crystalline form, graphite, for the fibres, and amorphous or glassy carbon for the matrix.

The useful properties of carbon-carbon include biocompatibility, thermal stability, high resistance to thermal shock (as a result of high thermal conductivity and low thermal expansion) and most importantly, high strength and stiffness at high temperature. Carbon-carbon is the leading light-weight refractory structural material (see Figure 2). Although carbon-carbon materials can withstand temperature of up to 3000°C in vacuum or inert atmospheres, they oxidise and sublime when in the presence of oxygen above about 400°C. Consequently for many applications (eg. long exposure to atomic oxygen in LEO space structures) oxidation protection must be used. Application of carbon-carbon materials in aerospace includes brake materials notably on Concorde and the Airbus, rocket nozzles and heat shields in re-entry vehicles.

Materials Influence on Cycle Thermodynamics

The above advances in the specific strength of materials at high temperature over the decade of the 1980's have resulted in the possibility of top cycle temperatures reaching the range 2000 to 3000 K (Figure 2), dependent on the level of insulation and component cooling employed. Since this is the case it is interesting to examine the ideal case of a Carnot cycle operating between some practical top temperature achieved by collecting solar energy and a bottom cycle (waste heat radiator) temperature optimised to minimise both the mass of the collector and the radiator.

That an optimum exists can be seen from the condition that as the radiator temperature rises it becomes smaller and lighter, whilst the increased heat rejected as waste means that more solar power must be collected thereby increasing the size and mass of the collector.

An example calculation of the relationship between top cycle temperature, size, efficiency and lower cycle temperature is shown in Figure 3.

Comparing the temperatures on this graph with the materials performance in Figure 2 we observe that carbon-carbon composites should have a strong influence in allowing high top cycle temperatures whilst the bottom cycle temperatures fall within the range of carbon fibre reinforced plastics and glasses. The effect of these materials therefore is to reduce the intrinsic

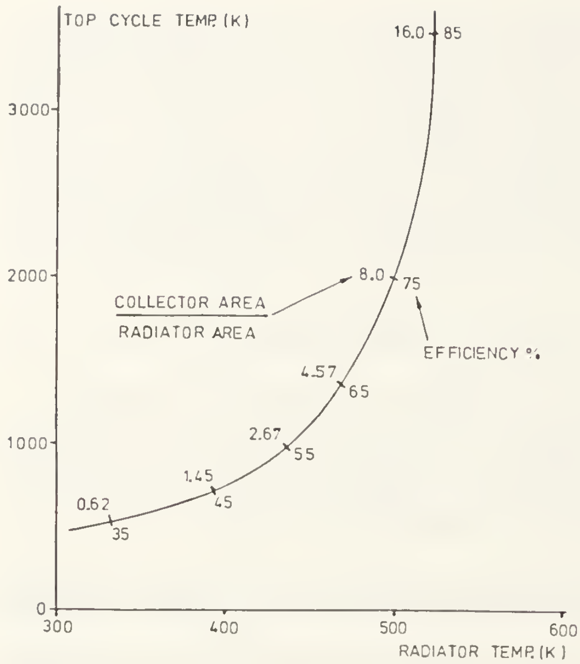

Figure 3 Effect of top cycle temperature on size, efficiency and lower cycle temperature of a solar heated generator

mass and the basic system size through more efficient conversion of sunlight to work.

A consequence of the limited range of materials available at high temperature is careful selection for chemical compatibility. Currently all high temperature high specific strength materials are carbon based above 1400 K and working fluids must be inert to this material. In view of the long lifetime requirements, say 50 years, this may exclude all but the noble gasses, implying that recuperated, reheated Brayton cycles may represent the only fluid cycle available if high reliability is to be achieved.

For conversion of shaft work into laser power it seems likely that electricity will have to be produced. High speed rotating machines which would minimise the turbine size would be a driving constraint and again composite materials should have a role to play.

Laser Type and Efficiency

Research programmes in inertial fusion, magnetic fusion and directed energy weapons have advanced the technologies that may contribute to the generation of very high power beams with good quality. In particular, the inertial fusion and laser weapons programmes have produced advances in the technologies of carbon dioxide, chemical (HF, DF, iodine), excimer (ArF, KrF, XeF, etc.) and free electron lasers (FEL).

In an FEL, a relativistic electron beam traverses a periodically alternating, static, transverse magnetic field (called the wiggler field, or undulator). The spontaneous emission (synchrotron radiation) of the electrons is responsible for the lasing action. In the course of the FEL interaction, this inherently broad band emission becomes peaked at a resonance wavelength due to a phase-matching process. The conversion of electron kinetic energy into the laser field occurs through the coupling of the forced transverse oscillations of the electrons in the wiggler to the transverse component of the laser field.

The basic characteristics of an FEL are quite different from those of conventional lasers, as the output wavelength can be chosen at will by adjusting one of the three macroscopic parameters ie. the electron energy, the wiggler period or the field strength. FELs have been operated at wavelengths between about 100 Å and 10 mm.

A further attraction of the FEL is the total system efficiency that can be achieved. Figure 4 shows some results for peak power output and efficiency of the Electron Laser Facility at Lawrence Livermore National Laboratory in the USA. A constant field configuration can produce about 200 MW at an efficiency of 6%. If a tapered wiggler field is used, such that the resonance condition remains satisfied for the original laser wavelength while the electron energy decreases along the wiggler, then powers of the order 1 GW can be produced with an intrinsic efficiency of 35%.

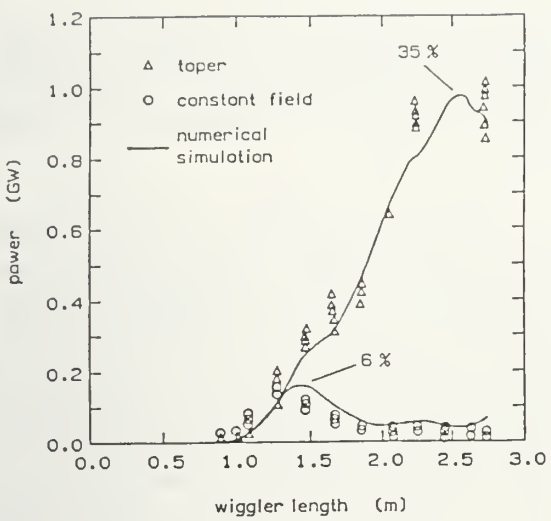

Figure 4 Performance of the Electron Laser Facility, with constant and tapered wiggler fields

For high power applications it is not the intrinsic FEL efficiency that is important, but the overall system efficiency. The unspent electron energy can be recovered, with 75% energy recovery having already been demonstrated and 90% levels anticipated for the near future. Even when the losses incurred in generating the electron beam are taken into account, overall system efficiencies of 50% or more should be attainable.

This efficiency value should be compared with estimated laser efficiencies of 20-25% used in the Lockheed (1978) study[1]. The use of an FEL with the above characteristics would result in space segment efficiencies in the range of 25% ie. almost double those used in the earlier studies. For a fixed output power this would result in a smaller total system (with impact upon the collector, energy exchanger, power conditioning and structure). While a detailed design of a space-based FEL will need to be carried out to estimate laser mass, there is nevertheless obviously considerable scope for reducing the overall mass of a system, compared to the masses quoted in Table 1 above.

Solar Collectors and Reflectors

In previous studies large orbiting flat solar reflectors have been considered for applications related to space power. Figure 5 shows one concept[7] for a one kilometre diameter version of such a reflector. This particular concept is well suited for deployable structures, and consists of a centrally telescoping mast and an outer deployable torus which is laterally supported by guy wires. The flat membrane is stretched inside the torus to form the reflecting surface. The areal density of such a structure would be of the order of 0.1 kg m^{-2} ie. a mass of about 80 tonnes. This is a significant reduction on the mass of the Lockheed collector (Table 1).

However, high performance solar concentrators require a dish-like, doubly curved surface to focus solar rays. The equation which governs the equilibrium of a membrane allows for two ways in which this can be achieved. The first case is one in which the membrane is loaded with a lateral pressure, and the loading is equilibrated with in-plane loads. Since a membrane has no bending stiffness the in-plane loads must be positive or equal to zero. Experiments have shown that a membrane surface must be stretched to eliminate wrinkles and develop a high performance reflecting surface. Thus for a membrane to achieve a high quality dish-shape it must be loaded with a lateral pressure.

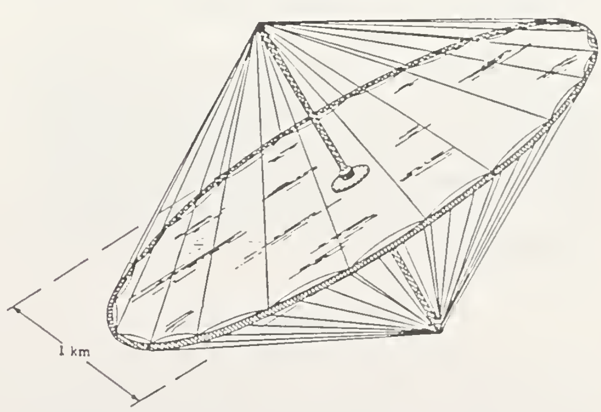

Figure 5 Schematic of a large diameter flat solar collector

The second case is one in which there is no lateral pressure. Here there are two possible ways to satisfy the equilibrium equation. Either the membrane is flat (both focusing radii are infinite), or one focusing radius is positive and the other is negative. The latter situation results in a saddle shaped membrane.

Inflatable solar concentrators have been under consideration for many years. Until recently, inflatable reflectors were not given serious consideration due to pressure leakage through micrometeoriod penetrations of the membrane film surface. However, Friese et al[8] have shown that for very large diameter concentrators, greater than 100 metres, the required inflation pressures are so low that leakage is very small. Thus, inflatable reflectors are good contenders for large solar concentrators. Mass curves have been given by Campbell et al[9], showing that this concept is extremely lightweight.

There are two main problems that remain unresolved with inflatable solar concentrators. First, the thin film surfaces must be formed from several metre-wide strips of thin plastic films. The seams between strips represent discontinuities in the film which result in local wrinkles which degrade reflector performance. Increasing the pressure to remove these wrinkles results in heavier concentrators. Secondly, the thin films used for these reflectors are some form of plastic, all of which have very high coefficients of thermal expansion. This inhibits making a stable, high precision solar concentrator.

Although the inflatable concept has some drawbacks, it is clearly worth continued research because of the potentially low masses that could result. Areal densities a factor of 2 or 3 lower than those estimated for flat reflectors may be possible.

Adaptive Optics

For space reflectors and concentrators, not only is there a requirement to reduce the mass of the structure to as low a value as possible, but the requirement on the temperature and stability of the structures in the space environment are increased considerably. A further complication with surface accuracy is given by the need to package the structure for launch and to deploy the system in orbit.

These difficulties over the use of rigid optical systems with large diameters have necessitated a search for fundamentally new design solutions and fabrication methods. Prospects in this area are favourable for structures where the fundamental requirement of high mechanical rigidity, necessary on Earth, loses its importance in the weightlessness of space. All reflectors intended for use in space can be constructed from thin, non-rigid shells if it can be guaranteed that their surface can be given the necessary shape.

The idea of sectional optical systems has been under study for some time, but the stringent requirements imposed on the accuracy and operating conditions could not be met until relatively recently. However, developments in computers, lasers and high-precision optoelectronic automatic systems now means that it is possible to control the position of individual elements of an optical array automatically with high accuracy, and to obtain a continuously accurate surface over the entire area. Such optical systems, the sections of which are in continuous motion during operation, are referred to as adaptive optics.

This concept of sectional adaptive optics makes it possible to satisfy all the basic requirements imposed on the construction of large reflective systems for use in space. First of all, it opens up the possibility of further reducing the mass, since all the advantages of light-weight one-piece construction can be realised. With an increase in mirror size for a given ratio of its diameter to thickness, the mass of the mirror will be reduced proportionately to the square root of the number of elements. Thus, for example, a 50 segment structure will have a lower mass by a factor of 7, compared with a one-piece structure.

Secondly, the problem of obtaining high rigidity is solved, as here only the rigidity of

individual elements is relevant, and this can be high for relatively small element dimensions. The problem of temperature stability is solved in a similar manner.

Thirdly the problem of obtaining and maintaining the required surface shape, to the necessary tolerances, is solved. The requirement for surface accuracy is imposed on an element of comparatively small size, and the accuracy of the entire structure is achieved by an automatic adjustment of the position of the individual elements, and the maintenance of this position during operation, by means of an automatic control system.

Finally, the problem of packaging such large structures for launch to orbit is also solved.

Summary

The application of current technology to the design of satellite power systems should lead to major reductions in the mass required for such systems, and to a corresponding reduction in the launch support necessary. This paper has given illustrative examples of the possible impact of technology advances, using a laser power system as a design case. Particular areas identified for discussion were materials advances, the influence of new materials upon cycle thermodynamics, laser type and efficiency, solar reflectors and collectors, and adaptive optics. It is concluded that there is large scope for significant mass reductions on satellite power systems.

Acknowledgement

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A5.2 On some new principles of SPS design

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There are at least two aspects of use of relativisitic MW devices for these purposes. First, there are relativistic electron devices of power of 1-10 MW, with potentially high efficiency and phase stability : relativistic clystron, gyrocone, gyrotron and some others. Its usage in CW impacts with problems, eg. heat withdrawal; nonetheless it would be justified - sharp reduction of number of necessary rf devices expedites the SPS design.

The second aspect is bounded with the possibility of employment of extra high power relativistic rf devices (of order of 1-10 GW). To date, the experimental devices operate with relatively low pulse duties (100-1000 nsec), but there are no principal restrictions to rise the pulse length. In this last case, the only one rf device for energy conversion is needed, the device being operated as a generator.

Besides that, there is a class of extra high power relativistic rf devices - so-called multiwave devices, which can bring off the forming of the antenna pattern diagram by themselves, as extra high directivity antennas. It simplifies (at least, principally), the SPS construction.

Pulse energy transmission from SPS has both independent and application-orientated interest; it might be useful in full-scale experiments on energy transmission from stationary SPS's with CW operation.

In SPS projects usually discussed, there are plane-phased array with aperture of about 1 * 1 km and large number of microwave amplifiers - klystrons or magnetrons of relatively low output power each, as the components. The paper presents the results of investigations of both the possibilities : to down in size the array aperture and, also, to use extra high power (up to 10 GW) relativistic microwave devices for energy transmission from SPS's.

First of all, it is necessary to note that, besides SPS "classic" version investigated in detail in many works, some new classes of energy transmission systems exist. In particular, pulse operating regimes are sometimes more convenient; besides that, diminishing of transmitting array aperture due to structural and/or some other considerations might be desirable. These "non-traditional" SPS schemes would be realized using recent achievements in high-current relativistic electronics and antenna design.

A5.3 Integrated Solar Power Satellites: An approach to low-mass space power

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Abstract

Previous concepts for solar power satellites have used conventional-technology photovoltaic arrays feeding a power collection and transmission system connected to microwave tubes used in a phased array antenna. This paper proposes using thin-film photovoltaics with an integrated solid-state phased-array to design an ultra-lightweight solar power satellite. The enabling technologies, conceptual designs, possible applications, and development steps are discussed. As these technologies evolve, their use results in a potential reduction in weight by a factor of ten to a hundred over conventional concepts for solar power satellites, and increases the utility by allowing service to smaller receivers at multiple receiving sites.

Les satellites à alimentation solaire intégrée : Une approche pour une alimentation dans l'espace de faible masse

Nous proposons un nouveau concept d'alimentation solaire de faible masse pour satellite qui utilise des cellules solaires à film mince et des transmetteurs intégrés dans la matière qui utilisent la technologie de matrice en phase. En utilisant cette technologie, il sera possible d'obtenir des diminutions de masse d'un facteur dix à cent par rapport aux concepts conventionnels.

Introduction

The concept of a Solar Power Satellite (SPS) to provide power for Earth was introduced in 1968[1]. Peter Glaser proposed to solve the energy crisis and provide abundant electrical power for Earth by putting large (1-10 Gigawatt) solar collectors into geosynchronous Earth orbit, and to transmit energy to the surface using a microwave beam. Solar power satellites based on this concept were extensively analyzed in the period 1978-1981 [2-4]. Solar cell technology has advanced rapidly in the last ten years, with improvements in efficiency, radiation tolerance, cost and weight. This has brought the status of photovoltaic technology remarkably close to the level predicted to be available by 1990 by the original SPS studies. At this point it may be of interest to consider new SPS design concepts to use emerging photovoltaic technologies which were not available at the time of the earlier SPS studies. These new technologies, along with improvements in RF and computational solid state electronics, allow the possibility of new and considerably better SPS designs.

The reference SPS design was developed using separate "rigid" photovoltaic arrays and microwave transmitting antenna. Significant problems encountered were the mass of the satellite, and associated transportation costs, and the need for high power levels, and thus high capital costs, to amortize the large antenna/rectenna required for efficient power transmission. In this paper we discuss a possible way to reduce these problems by integrating the solar cells and microwave transmitter/antenna into monolithic building block units. These units may then be replicated as desired to create a structure whose light collection area is also used as the transmitting aperture. The total satellite mass could thus be reduced by eliminating antenna structural elements and a majority of the power conditioning and distribution wiring. Further, because of the larger aperture, this integration could yield a narrower microwave beam at the receiver(s), at much lower power levels, allowing smaller unit size power satellites.

Micro-phased array distributed SPS

In the highly-integrated SPS design proposed [5], microwave oscillators and dipole antennas are integrated directly with the solar cells, using phased-array techniques to steer the beam to the receiving antenna(s). Rather than a smaller number of high-power (kw's) microwave tubes, the integrated SPS will have hundreds of thousands to billions of self powered integrated transmitters, each operating at low power. This integration would eliminate the power conditioning elements and the wiring used for power distribution, reduce the waste thermal management subsystem to small self-contained radiating surfaces, and eliminate a separate discrete antenna.

The state of technology development in solid state electronics and solar cells indicate that such an integration could be performed. It may even be possible to design a solar power satellite to be

constructed entirely by thin-film technology, consisting of thin (one to two micron) active components on a plastic substrate. The potential thus exists for technologies currently under development, thin-film photovoltaics and solid state microwave and computational electronics, to considerably reduce the mass-to-orbit required for such a satellite power system.

The proposal consists of the following elements:

--Total integration. Microwave transmitters are integrated directly at the solar cell level. No wires or power management/distribution system is required.

--Thin-film construction. Lightweight photovoltaic films, and possibly thin film microwave devices, on a thin plastic substrate are used. The structure likewise is not a heavy "rigid" unit, but rather of light weight flexible construction.

--Phased array antenna. The antenna does not need to be physically "aimed" at the receiver but is steered by controlling each element's phase.

The distributed thin-film SPS applies the integrated circuit approach to the satellite solar power concept. By designing small, relatively complex building blocks (i.e. self powered transmitters), and replicating them many times over, the total system is constructed. This allows the design, development, and testing to be performed at this small block level, and the manufacturing done on a high volume item. Integration and control of these building blocks in a total system will be critical. Two major areas to be considered are physical construction of the satellite and control of the phased arrays.

This paper discusses the status of the enabling technologies for an integrated solar cell/transmitter approach, conceptual designs of solar power satellites that use such an approach, possible applications, and development needed.

Thin film photovoltaics

In the 1980's considerable research was devoted to development and commercialization of thin-film photovoltaics for terrestrial power generation. Thin-film solar cells consist of thin (~1-5 μm) films of photovoltaic material deposited on a supporting substrate. Efficiencies around ten percent have been achieved with amorphous silicon and copper indium diselenide thin-films, and encouraging results from other thin-film technologies such as CdTe and $CuInS_2$. Table 1 shows the historical progress in efficiency of several of the thin-film materials over the last few years [6]. This compares to typical space qualified cell efficiency of about 14% for currently used silicon cells, 19% for GaAs cells, and projections of over 20% efficiency for cells to be used in the 1990's.

Because of the high optical absorption constant of these materials, the active material may be as thin as one to two microns, inherently yielding extremely lightweight cells. However, very little current research is aimed at depositing thin-film cells on lightweight substrates, since most of the applications being considered are terrestrial, where weight is not as critical. To enable their use in space, technology for deposition on extremely lightweight substrates will need to be developed.

Table 1. **Historical progress of thin-film solar cell efficiency.**
Experimentally achieved efficiencies (extrapolated to AM0, in %) as of 1978, 1983, 1988, and projected values for future performance.

Material	1978	1982	1988	1990's
CdS/Cu_2S	7.3	8.2	9.	10
$CuInSe_2$	5.3	8.5	11.2	12
$CuGaSe_2$	-	-	4.6	12.5
$CuInS_2$	2.9	2.9	6.1	12.5
CdTe	4.1	8.4	8.6*	12.5
a-Si	4.4	8.1	9.0	11.5
CASCADES	-	-	12.5	17+

*(9.8% reported in May 1989)

An extremely conservative projection of space thin-film solar cell technology would be a 5% efficient thin-film cell fabricated on a 25 micron thick Kapton substrate. This yields a photovoltaic blanket specific power of 1.7 kW/kg. An optimistic projection might be a 15% thin-film cell on a 7 micron thick Kapton substrate, leading to a photovoltaic blanket specific power of 15 kW/kg. These numbers compare favorably to current state of the art spacecraft solar blankets, *e.g.*, 67 W/kg at the array level for the flight-tested SAFE array, and 130 W/kg at the array level for the experimental APSA array using thin silicon solar cells. Values for the photovoltaic blanket alone without the array structure are about twice as high.

Thin film cells have other desirable features for space applications. In addition to low mass, thin-film photovoltaics are also projected to have considerably lower costs. Materials cost is reduced due to the small amount of materials required; the cost of labor and assembly is reduced by the fact that large-area, integrated assemblies are produced directly on the substrate sheet. Preliminary results also indicate thin-film solar cells may be inherently radiation tolerant, and not require a glass cover for radiation protection [7]. They are highly tolerant of small damage areas, such as damage due to micrometeorite or debris impact.

For currently designed space power systems, the photovoltaic blanket weight is only about a quarter of the total power system mass, as shown in table 2. The array structure and the power management and distribution (PMAD) system account for three-quarters of the power system mass. This provides a powerful incentive to reduce or eliminate the PMAD by integrating the loads (RF elements)

directly in the solar array, and to design new array structures to take advantage of the ultralight blankets. The full utilization of the thin-film cell's low mass potential is a goal of the proposed integrated design.

Table 2. **Space Station *Freedom* Photovoltaic Power System Mass Breakdown per module**
(28 kW power produced;
18.75 kW av. user power)

Element	*Mass (kg)*	*Fraction (%)*
PV Blanket	890	24.0
mast	330	8.8
gimbal	540	14.5
electrical equip.	610	16.6
thermal control	730	19.6
misc. integration	610	16.5
total	*3710*	*100*

not including:

Batteries:	1300
Charge/disc. unit	290

Array is a quarter of system mass
array plus structure is half of system mass

Microwave electronics

Use of thin-film solar cells will significantly reduce the satellite mass only if the mass required for the power management and the microwave beaming system can be reduced as well. This may be achievable using solid state electronics. In the last ten years we have seen development of microwave integrated circuits, thin-film transistors, and thin-film microwave rectennas

Since solid-state electronics has developed considerably, it is now reasonable to consider using them instead of tubes as the microwave source for a SPS. Tubes are well developed, and have been the DC to RF converter of choice for most high power applications. However, use of microwave tubes requires the electrical power to be collected from the photovoltaic array on the SPS and distributed to them, and their waste thermal energy transported away. A distributed solid state network of DC to RF devices operating at much lower power densities could greatly reduce or eliminate these supporting power and thermal transport subsystems.

Microwave rectifying antennas (rectennas) for receiving microwave power and converting it to DC power have been demonstrated using thin-film techniques on a thin-plastic substrate [8]. Using such a technology as a microwave source requires replacement of the rectenna GaAs diodes by appropriately phased solid-state microwave generators. Similar solid state devices and phased arrays are being developed for communication and radar applications, *e.g.*, conformal antennas on aircraft skins, drivers for large aperture radars, space communications phased arrays.

An extension of this type of phased array closely couples the distributed power source, *i.e.*, solar cells, with the RF generator and antenna. Such a concept for integration of the solar cell with the microwave oscillator and antenna is shown schematically in figure 1. A slightly more complex version, where the solar cell metallization could possibly be used for the antenna in a "push-pull" configuration, is shown conceptually in figure 2. What is created is a self powered RF transmitter that converts sunlight in to RF out. For the SPS design being discussed the output beam is received for power. It could just as well be for communications, radar or other uses *e.g.* a self powered RF repeater. These uses will not be addressed in this paper.

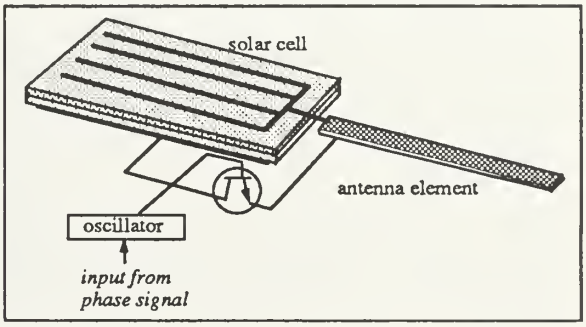

Figure 1. *Solar cell with integrated microwave antenna element (conceptual diagram).*

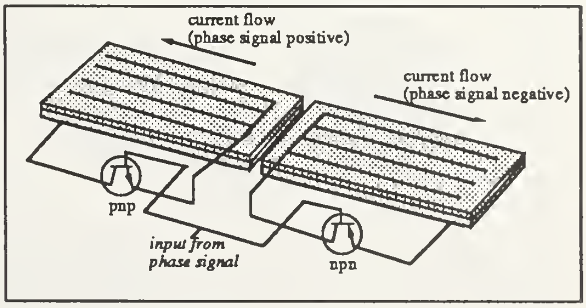

Figure 2. *Conceptual diagram for integrated solar cell/transmitter combination in a push-pull configuration. The contact metallization of the solar cells serves as the antenna element for the integrated microwave transmitter. Complementary pnp and npn transistors receive the same phase signal.*

Microwave integrated circuits are currently available which can operate in the gigaherz band proposed for SPS power transmission, and have been demonstrated by many different laboratories for operation at the tens and hundreds of gigaherz [9]. In a possible near-term design, the microwave integrated circuits are fabricated separately and then bonded to either single crystal or thin film solar cells. Using single-crystal solar cells, a more

advanced design with microwave ICs fabricated directly on the cell could be a logical next step.

The future extension of the design would construct the entire integrated unit using thin-film technology. Thin-film microwave electronics are a reasonable extrapolation of the union of two recent developments: solid-state microwave electronics, and thin-film transistors. Thin-film transistors have been developed for other applications such as display screens, where many millions of devices have been integrated on a large-area sheet. Current technology only allows frequencies in the range of kiloherz to at most megaherz [10], but this will likely increase with further research. Development of gigahertz-speed thin-film transistors would allow the transmitter elements to be deposited on the thin substrate at the same time as, and possibly using the same materials as, the thin-film solar cells.

Conceptual structural designs

It is important to design new, low mass structures in order to reduce the structural mass of the system proportionately to the photovoltaic and transmitter mass reductions. Many structural designs for such a system are possible. Two, the "bicycle wheel" configuration (figure 3) and the "sphere" configuration (figure 4), are shown. Using a phased array means the microwave antenna does not have to face directly toward the receiving station, as long as the antenna is not edge-on to the receiver.

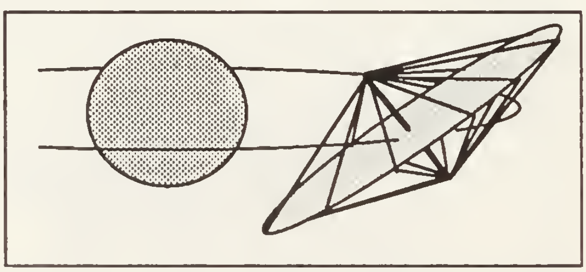

Figure 3. "Bicycle Wheel" configuration for a thin-film SPS.

The "bicycle wheel" concept could use centrifugal force to place a thin circular membrane of integrated transmitters in tension. Since the size is large and the tension required small, a very low rotation rate, <<1 RPM, is sufficient to provide tension. Bracing cables from a central hub provide the requisite out-of-plane stiffness. If necessary, a counter-rotating flywheel can compensate for angular momentum. Alternately, the rotation is not required if beams are used instead of wires or an inflated torus (tire) is used to provide the tension.

In the sphere configuration, the solar cell/microwave transmitter elements cover the surface of an inflated sphere as in the Echo satellite or are on a film stretched across the sphere. For a sphere radius of many hundreds of meters the surface/volume ratio is extremely low, and the gas pressure required to hold the form, and the associated leak rate, can be made small.

If a planar solar array is not normal to the sun, there will a decrease in power proportional to the cosine of the solar angle. Likewise, if the transmitted beam at the receiver is larger than the receiver rectenna, there will be a cosine-dependant decrease in the fraction of power received when the transmitter array is not pointed directly at the receiver, there will also be a cosine dependent decrease in the effective transmitter aperature. A first look at a satellite in an inclined continuous sun orbit around the moon at 900 Km altitude beaming to a base on the lunar surface indicates that the combined "cosine loss" from a non-tracking array is approximately 30%. In addition to this loss would be other off-axis effects due to inefficient operation of the antenna elements. Thin-film PV elements are light enough that high power to weight ratios may be maintained even if they do not track the sun and must be oversized to compensate for these losses. An alternative would be to use a lightweight turning mirror to redirect the light from the sun to an integrated array pointing toward the receiver(s). These options need to be evaluated in a more extensive system study.

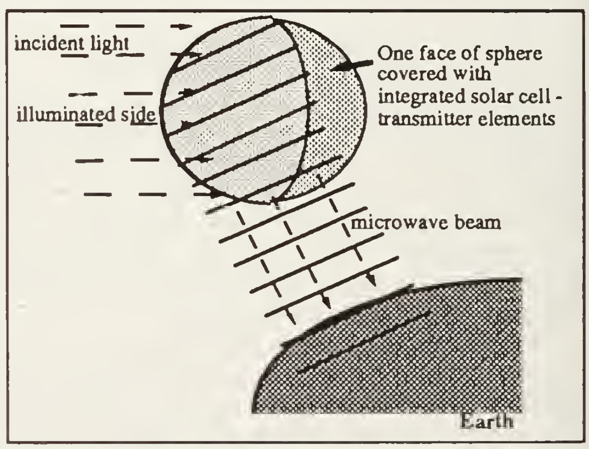

Figure 4. Inflatable sphere configuration for a thin-film solar power satellite.

Phased array control

Phased array technology uses "electronic steering" instead of mechanical pointing to direct the output beam to the receiving array(s). One approach would use a pilot beam from the receiver(s), which is received and phase-conjugated by the transmitter to create an output beam precisely reversed from the incident pilot beam. This requires no overall processing capability except for the ability to maintain a synchronized clock to measure the phase. Each individual output element is required to adjust its phase to sum coherently into the output beam. Each element

receives the pilot beam, compares the pilot beam phase with the reference (master) clock, and adjusts its output beam to conjugate the phase: *i.e.*, the output oscillator phase is to be exactly as far behind the reference clock zero as the pilot beam phase is ahead of the reference clock zero. This phased array control approach thus has three parts: (1) maintaining the reference clock, (2) receiving the pilot beam, (3) setting the proper element phase.

For a rigid array using a central clock, the local reference signal consists of the central signal compensated for the "fixed" transmission delays. The difficulty of synchronizing the local clock references increases if the array is not rigid, since the distance to the central clock, and thus transmission delays, may vary. In this case a means to measure the elements displacement, such as a laser interferometer, may be used to compensate the delay.

It is also possible to provide each individual element with an oscillator to use as a clock to compare phases. To maintain coherence of the output beams, all of the clock oscillators must be synchronized in both frequency and phase. If the local oscillators drift from the correct phase with a characteristic drift time t ($\approx 1/\Delta f$, where Δf is the error in frequency), their phase must be reset on a time scale short compared to the drift time. Clearly, the more stable the local oscillators, the less often they need to be reset.

The pilot beam need not necessarily be at the same frequency as the transmitted beam unless a mixing technique (*e.g.*, a four wave mixer) is used to generate the phase-conjugation. A pilot beam at, or near, the same frequency as the power beam has the advantage of automatically correcting for atmospheric effects. A disadvantage of a pilot beam at the output frequency is the difficulty of distinguishing pilot beam from output (*e.g.*, by polarization difference). Failure to adequately isolate the pilot beam from the output beam would result in undesirable self-stimulated oscillations of the transmitter.

Any beam which can provide timing information with sufficient accuracy can be used; for example, the pilot beam can be a microwave beam at many times higher frequency. An interesting alternative is to use a pulsed laser as the pilot beam. Techniques now exist to make laser pulses with durations of picoseconds and shorter; sufficiently fast to use for microwave frequencies up to hundreds of gigaherz. Each laser pulse would be used to set the phase signal. A variant of this approach would be to use a laser pilot beam which is modulated at the microwave frequency.

The system architecture is simpler if the pilot beam and master clock can be eliminated. This alternative is possible if the adjustment of the phase of the output oscillators is done using information from the receiver antenna.Without a pilot beam, the local phase must also be continually adjusted to compensate for the fact that the individual elements relocate in position due to flexing and rotation of the array. If the elements move at a velocity v, the oscillators must be reset on a time scale short compared to the time it takes the elements to move the distance of a wavelength, or a time scale of (v/c) f.

The oscillator drift time must be long compared to the round-trip delay between the transmitter and the receiver. In this case the receiver antenna can generate the information required to reset the local oscillators. There are many possible approaches for doing this. In the following discussion, we assume: (1) low-drift local oscillators, (2) a master-computer with the capability of addressing each individual oscillator, (3) simple computation capacity at each oscillator.

The simplest information for the receiver antenna to generate is the spot size and center location of the beam. Using this information, the master computer could then continuously tune each individual oscillator to minimize the spot size and keep it centered on the receiver, by sending each individual oscillator a message "advance/delay your phase by Δt".

Clearly, with a number of oscillators on the scale of $\sim 10^8$, adjusting the phase of any individual oscillator will not contribute significantly to changes in the spot, i.e. the signal to noise ratio would be too low. A technique must be used to adjust the oscillators globally. For example, linearly delaying the phase of the oscillators across the aperture would have the effect of slewing the beam. Focussing the spot could be done by adjusting the oscillator phase in fourier harmonics; *e.g.*, commanding each oscillator to delay its phase by an amount $\Delta t \cos(nx/d)$, where x is the x-coördinate of the oscillator, d the diameter of the satellite, and n the order of the fourier harmonic. If this decreases the spot size, the change would be kept; if it increases the spot size a change the other direction would be tested. Many techniques exist for finding the global optimum. Terms in sin(x), sin(y) and cos(y) must likewise be optimized. Use of distributed intelligence at each element will allow considerable simplification of the design.

Since the system must adjust a number of degrees of freedom equal to the number of oscillators, $N \sim 10^8$, the minimum time required is N/f, *e.g.*, for a 10 GHz beam, $t > 10^8/(10^9 \text{ sec}^{-1}) = 0.1$ seconds. In practice it would be impossible to calculate the spot diameter as fast as once per cycle, and a minimum update time could require more like 10^3 cycles; thus, an update time ~100 seconds. For the 10 GHz system this means that the oscillators must drift no more than $\Delta f/f < 10^{-12}$.

Given computational capability, each oscillator can predict its drift and use this information to calculate and correct the expected drift. The control system will only be needed to calculate the difference between the calculated oscillator drift and the actual drift. Using this technique, it may be

possible to keep the oscillator stability to $\Delta f/f<10^{12}$. Given the capabilities of a super-computer, it would be possible to keep an overall dynamic model of the system, with information on the characteristics of each oscillator continuously updated from the information available. The master computer could then be used to update the correction factor for each oscillator.

More extensive measurement and calculation on the receiving antenna could simplify this procedure considerably. In principle the receiving antenna can generate information on the phase and intensity of the received beam at every location on the ground antenna. This results in a two-dimensional map of two independent variables, which can be used to readjust the transmitter phases to minimize the spot size. The transmitting antenna has 5 local variables: the phase and intensity of each local oscillator, and the x, y, and z location of each oscillator on the (flexible) structure. These are not independent degrees of freedom. The oscillator phase delay can be exactly translated into an equivalent distance. The oscillator location is further subject to two constraints, since the transmitter elements are arranged in a two-dimensional array. This leads to at most two independent degrees of freedom for each oscillator. The two-dimensional information from the receiver are thus, in principle, sufficient to calculate the transmitter phase corrections needed. Once the nearly-correct phase is established, with perhaps a dynamic model of the transmitter, it should be possible for the fine phase adjustment to be generated relatively rapidly.

It should be noted that the phasing difficulty is not significantly increased if the transmitting array is to beam to more than one receiving site. In this case the transmitter output is the linear superposition of that which would be required for each individual output beam. This could be accomplished by having each receiving station send a pilot beam, or alternatively, each receiver could sent phase and intensity information to the master controller, which then optimizes the output phase to put the required amount of power on each receiver. If the exact location of each receiver is known and the dynamic model of the system is good enough, the wavefront measurement and computation could all be done at one receiver.

Discussion

Table 3 shows a comparison of the mass of an integrated thin-film solar power satellite compared to the SPS system baselined in the 1980's. Using the "conservative" technology extrapolation the reduction in weight is more than a factor of ten; assuming a more advanced technology, a reduction in weight by over a factor of a hundred is possible.

Baseline SPS (1980):	
2.6 kg/kW	Transmission and control
6.5 kg/kW	Silicon Solar Array
0.6 kg/kW	Power Conditioning
9.7 kg/kW	
Thin-Film SPS (1990's):	
(5% efficient solar cell on 25μ Kapton)	
0.7 kg/kW	Solar array + integrated transmitter
Thin-Film SPS (2000+):	
(15% efficient solar cell on 7μ Kapton)	
0.08 kg/kW	Solar array + integrated transmitter

Table 3: *Mass Comparison of Integrated Thin-film Solar Power Satellite Concept with Baseline Design*

Since the integrated design provides a transmitting aperture the size of the photovoltaic array, not only is there potential for reduced mass, but there is also the possibility to achieve "economic breakeven" at a considerably reduced power level. The baseline SPS concept used a 1 square kilometer transmitting antenna and a 102 square kilometer receiving rectenna. To amortize the cost of the large antennas required, a 5,000 Mw (output to user) power level was proposed. An integrated SPS design using the same sized rectenna and transmitting aperture as the baseline, assuming the same system efficiency, would allow a minimum power level of only 33 Mw [using the 1990s assumptions above] or 100 Mw [using the 2000+ assumptions]. For higher power levels (*i.e.*, a larger transmitter aperture), a smaller rectenna could be used. For example, at the 5 Gw level proposed for the 1980 reference SPS [4], the integrated array/transmitter would allow the rectenna area to be reduced by a factor of 50 to 150, resulting in a required rectenna area of only 2 or .67 km^2 respectively using the far-term and near-term assumptions. Such power levels, although representing absolute intensity of only a few times that of the sun, could be too high for single user operation; but multiple users, each with these smaller receivers, could share the power either by "spot beam hopping" or by simultaneous transmission as discussed. The use of an integrated design, with potentially very large transmitter apertures, thus enables new system architectures providing power to smaller receivers at multiple sites.

Applications

The main application of the solar power satellite envisioned by Glaser and by many of the later advocates of satellite solar power was to provide baseline electrical power for terrestrial use. However, it is quite likely that some of the most important applications, and certainly some of the initial applications, will be in space. Here atmospheric attentuation does not limit the frequency choices and transmission distances may be less. Further, because of the high total mass of the power systems (including storage, PMAD, thermal control and structures) and the high transportation costs, existing power sources for use in space provide power at a considerably higher effective price ($800/kWhr) than terrestrial power sources ($.10/kWhr) [12]. By building integrated solar power satellites, remote power sources would be able to serve several critical needs. These include:

(1) Beamed power for lunar bases, rovers, remote instruments, outposts, etc.[13]

(2) Remote powering of electric propulsion vehicles, *e.g.,* for inter-orbital transport vehicles using ion or magnetoplasmadynamic engines.

(3) Power for Earth-orbital stations [14]

(4) Support for Mars missions and solar system exploration and exploitation.

Developments required

So far we have only discussed the potential advantages, and not the problems. The concepts outlined above have been schematic, not detailed engineering designs of how such a system could be built. Many problem areas remain to be addressed. We will only briefly identify some of the issues here, without attempting to detail all of the possible approaches, and suggest some development steps required.

The issues involved with providing a reference clock signal and distributing the proper phase signal to a non-rigid array have been only superficially addressed. This could be done either with analog processing or with digital circuitry. The difficulty of this problem is decreased if significant amounts of integrated processing capability is available at low cost.

If the elements are equipped with local oscillators, then the phase signal is only required to keep the local oscillators in correct phase. If the system does not have local oscillators, or if the local oscillators have poor frequency stability, a continuous phase signal is needed.

A full design of the microwave antenna and its integration with the RF generator and solar cell including such issues as backplane construction needs to be performed. Antenna elements have radiation patterns that yield best efficiency at a given angle. Off-angle losses and polarization issues need to be addressed.

Solid-state RF generation technology issues will need to be addressed in order to verify that manufacturable devices can meet the efficiency and reliability goals required for a SPS.

In general, the problem areas appear amenable to technology and engineering solutions. The important question is whether resolution of the problem areas would unacceptably increase the complexity, weight, or cost of the system. To this end system analysis needs to be performed to determine the technical and economic feasibility of the concept. If feasible, design, development and demonstration of the integrated solar cell/transmitter/antenna building blocks, possibly as a self powered RF repeater, should be undertaken. Finally integration of the building blocks and other support systems into a flight demonstration/ and or first application could lay the groundwork for low mass space power by use of integrated solar power satellites.

Conclusions

Thin-film photovoltaic arrays, microwave solid-state devices, and increasing computational technology have the potential to create a revolutionary change in solar power satellite design, with possible improvements in power to weight ratio of a factor of ten to a hundred. Thin-film photovoltaics alone could yield a notable improvement in mass; however, to take full advantage of the technologies being developed, we have proposed a design for a fully integrated photovoltaic/microwave system, where the phased array microwave elements are integrated with the solar cells, eliminating all the power management and distribution, reducing the waste thermal management subsystem, and eliminating a separate discrete antenna. To take advantage of this design, small self-powered transmitter "building blocks" will need to be designed, developed and tested. Further, the control of these elements and their integration in a light weight structure will need to be performed. If this could be done, many new applications, especially those with small receivers at multiple locations can be visualized. The concept of integrated solar power satellites thus raises the potential for low mass (*i.e.,* lower cost) space power.

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A5.4 Future aera for SPS: "Donor-Acceptor" type power supply system for isolated and mobile consumers

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ABSTRACT

Unconventional types of SPS energy consumers are proposed. To provide them with electrical and heat energy, a low orbit SPS system has been designed. Due to the combined production of energy for consumers, microwave and laser transmission efficiencies are comparable. The low level of SPS power and using laser transmission could demonstrate the SPS system on a small-scale, not influencing biota and existing communications.

RESUME

Dans cet article, l'auteur fait le point sur les perspectives de l'évolution de l'alimentation en énergie thermique et électrique de consommateurs non traditionnels par l'utilisation de systèmes SPS situés sur orbite basse. Grâce à la production combinée de l'énergie, l'efficacité de la transmission en microondes est proche de celle utilisant des faisceaux laser. Le bas niveau de la puissance du SPS et l'utilisation de la transmission par faisceau laser constituent une démonstration à échelle réduite d'un système SPS, sans effet nuisible.

INTRODUCTION

The original concept for a Solar Power Satellite (SPS) was proposed by Peter Glaser over two decades ago[1]. SPS utilized the microwave beam to bring solar energy collected at a geostationary orbit to terrestrial consumers.

Recently, considerable interest has been focused on the possible use of lasers for this purpose[2]. Lasers can create extremely narrow beams, using much smaller transmitter as well as reception apertures. Using coherent optical adaptive techniques, an optical system based on wave-front conjugation would direct laser radiation even to the required moving receiver. These advantages create the possibility in principle to supply power small isolated consumers, and in the future to feed mobile consumers[3].

The result of the CDEP program carried out by DOE and NASA had shown that the straightforward approach to the realization of a microwave SPS as a large-scaled object has practically no solution. The application of the SPS for power supplying of customers having already got feeding from existing highly developed power system would be unlikely economically justified in the distant future. Moreover, microwave beam sidelobes might interfere with communication and have adverse impact on living organisms[4].

The high capital investment necessary for a full-scale SPS system requires assessing, verification of the SPS technology, as the SPS creation is associated with high risk, if not to follow strictly step by step a SPS program. Therefore, it would be natural to make the following step in developing of the small-scale laser SPS conception. This step might be an attempt to use the advantages or unique qualities that make SPS different from traditional energy supplying competitors.

In the paper an attempt is made to substantiate the expediency of using such a unique quality of the SPS as flexibility of space position control of a ray in beam transmission. The quality is most purely and brightly expressed for a laser beam operating.

Mobile and isolated loads in the Arctic are taken as probable consumers of SPS energy because they are now fed from power supply sources that are the poorest economically. Moreover, these loads are small comprising from 5 to 400 kW. This is a nice example to create small SPS for purposes of demonstration. In addition, a power failure results in hard consequences for the arctic consumers. This demands a power supply redundancy also.

High fuel delivery costs, advances in beam technology, a mature space industry and the problem of sensitive arctic environment would make a SPS-powered arctic substation even cost-effective in comparison to tomorrow's advanced diesel. (SPS would pollute the atmosphere much less than present diesel engine)

SPS consumer choice

In this paper the SPS concept is developed pertinent to the problem of supplying power to isolated consumers along the arctic shore of the USSR, USA and Canada. As a rule, the consumers are remote from power centers, they are powered with a fossil fuels and have self-contained power supply.

The consumers need both electric power and heat. Such of consumer selecting would permit to reach economic justification of laser SPS, as heat requirement of these consumers allows to utilize the heat waste of a laser energy conversion to electric power. In addition to, considerable

improvements in a laser and optic technology will have resulted the laser SPS might be even economically competitive with existing diesel at lower fuel cost.

The SPS is intended for power supply of the most typical arctic isolated consumers. By year 2010 the average load will comprise 30 kW of electrical power (for an 8-hour operating period on the average) and $3*10^5$ B.T.U/hr of heat.

For a time of a test operation of incomplete SPS system, the SPS network might be used in order to reduce the amount of fuel that has to be delivered to remote isolated consumers in arctic regions, and the SPS will have to operate with an emergency engine in parallel. In general, the SPS system is intended to serve about 150 consumers distributed along the arctic shore.

The main characteristics of such consumers are the large degree of irregularity of daily power consumption and high requirements on reliability. The proposed "donor-accepter" type SPS system could satisfy these requirements.

I. SPS NETWORK DESCRIPTION

The system is formed out of fourteen small -scale SPS which are placed on low (925-km attitude) periodic orbits and have:

- converted solar energy accumulators,
- power connections between individual SPS.

The system is based on two principles:

- periodically each SPS is interconnected to any one consumer to provide power supply reliability;
- periodically energy between accumulators of individual SPS is exchanged by beam transmissions. So energy resources are redistributed among the supplied consumers to satisfy their daily power consumption.

Orbit scheme

For realization of the proposed scheme the SPS have to travel periodical orbits. Their planes have to pass through a common axis of the symmetrical orbits (the axis of revolution of the Earth, for example). Besides, every SPS group must be synchronized with respect to the crossing point of symmetrical orbits which is located over the north and south poles. Unfortunately, to provide natural pulling of whole SPS into synchronism, gravitation forces between several SPS are too negligible at the meeting points.

In order to compensate for regular precession of SPS orbits and to synchronize them with the Sun, the whole SPS are placed at 925-km altitude circular orbits at 95° inclination and as a result they would easy beam a laser energy to the terrestrial consumers of arctic region, mainly. For simplicity, we will suggest they have the strict polar orbits. Due to the proper choice of SPS attitude, it is taken into account that severe radiation degradation from exposure with the Van Allen Belts in low orbits would not rule out photovoltaic cells application.

SPS interaction within system

Along sections of SPS orbits that come closest together energy is intensively (about 300sec-duration and 12 MW power) exchanged between SPS accumulators within a synchronized SPS group. The program of energy exchange between the next "SPS-donor" and "SPS-accepter" is determined by power consumption conditions of the terrestrial consumers will be served at the current orbit corresponding SPS.

The SPS are differed from each another. The three heavy base Sun-synchronous SPS have 2MW mean output power , and eleven light energy-transporting Sun-stationary SPS - 400kW. All small SPS go into regular to the Earth's shadow and as a result they need in receiving the required by them storage of energy from heavy Sun-synchronous SPS before the light SPS will have travel to the Earth's shadow. However, it is very important to note, that the loads consume only 20 % of their base power operation, when the SPS serves them along shadow path of the orbit.

A group of synchronized SPS is placed on low orbits in order to pass the certain section in the orbits over the regions of dislocation of consumers that also have electric and heat energy accumulators.

If along the current orbit path, the consumers are absent (the SPS travels over an ocean or in the case of heavy cloud cover of the reception sites) or their current loads are small, the SPS gives its stored energy to another one at the point of the SPS spatial synchronism (over the poles).

Interaction SPS with consumers

As a result due to the Earth revolution and by selecting the periodical SPS orbits, the SPS will remain over south polar, but already for the next consumers, which have been already served by previous SPS. Because, the failure of any given SPS will require no considerable additional margin of diesel fuel, since next SPS unit could be switched to the unserved substation.

If an atmosphere canal is transparent and power is required to consumer, the SPS laser would track reception substation, lock on, and beam a laser energy to it. The ground substation would be tracked by skin echo from cataphote (corner reflector) which is placed in the center of the reception mirror. To track the substation mirror, wave -front of a reflected beam part is conjugated by means of laser adaptive optics, after removing to the SPS.

The consumer accumulators get their charge from the SPS when they travel through the corresponding section of SPS orbital path (150sec-duration). Accumulative capacity, about 50 kW*hr, has to correspond both to the interval (24/14 hr) between seances with the consumers and, to their base load. Consumer peak power is provided with emergency reserve switched in parallel.

Terrestrial reception substations of laser power transmission could use thermo-photovoltaic conversion in parallel with thermal cycle, executed by means of concentrating mirrors. Laser energy conversion into electric power results in considerable heat waste. This loss, is assumed, to be utilized for central hot-water heating of the arctic consumers. Unlike for microwave, here it is possible due to a short distance between laser reception substation and heat consumers as a buffer zone of safety would be small for the reception substation of the laser SPS.

Table 1. summarizes some of the most important characteristics of the SPS system.

Table 1. Characteristics of the SPS network

	light SPS	heavy SPS
Number SPS	11	3
Number served:		
consumers	10	17
SPS	–	8
Output	400 kW	5(2)MW
Orbit SPS:		
altitude	925 km	925 km
period	1.72 hr	1.72 hr
inclination	95'	95'

II. SPS CONVERSION PROCESS LOGIC

In principle, scheme contours of the SPS and ground substation are certainly defined both with an arctic load selection, and with a energy exchange executing within framework of the SPS network itself.

In fact, to meet the consumer heat demands using the heat loss of beam energy conversion to electric power, a distance between reception substation and the heat loads has to be short. This rules out employment of microwave transmission, which requires a large buffer zone of safety. The laser transmission , meeting the mentioned demands, permits also to execute the energy exchange between several SPS.

In it's turn, to operate the laser, which has relatively low temperature of heat waste, the large area for the radiating cooling is required. In general, the use of forced cooling for the lasers has led to a choice of thermal cycle of a solar energy conversion. Moreover, to restrict to a reasonable size of a common radiator area of laser and a thermal cycle, high-temperature Rankine cycle has certainly to be adopted.

The ground substation scheme is certainly defined too with:
- a pulsed operation of laser energy conversion,
- relatively low power level,
- high temperature input, potentially, of the conversion cycle,

and with usage of forced water-cooling for purposes of arctic consumer heating.
This factors have led to a choice of Stirling's thermal cycle.

Application of high-temperature thermal cycle for both the SPS and the ground reception substation permits to initiate them by direct conversion of a concentrated radiation energy.

Laser beam propagation

Space power transmission with a laser beam results in several diffraction divergence of a pencil beam, only. Therefore, an energy loss is absent there. Due to a beam diffraction, the laser transmission would require a 5-m-diam transmitter aperture for a 6-m-diam spot at a 1000 km range (30° zenith angular is assumed for 925 km SPS attitude).

Even taking into account several thermal blooming of the laser beam, small reception aperture would permit to make the SPS substation in the form of transportable variant.
Unlike space conditions, in atmosphere the propagation characteristics depend on various meteorological conditions[6].

Active optics system uses active computer control of transducers to shape the optical surface, allowing correction of mirror distortion, thermal blooming and pointing errors. Beam atmospheric disturbances on the unlink can be greatly ameliorated by cooperative adaptive optics deriving correction signals from reflected beam leading the main beam slightly in the direction of motion through the atmosphere.

Table 2. Transmitting laser characteristics

Output power	2 MW (12)
Working cycle duration	150-300 s
Adaptive reflector:	
diameter	5m
reflectiveness	99.5
Operating temperature	350-500 K
Efficiency	30 %
Wavelength	10.6(2.2)µm
Tracking accuracy	10^{-8} rad
Specific mass	6 kg/kW

III. SPS PERFORMANCE

Independently on the SPS kind, each SPS consists of four components, namely:
1) three-mirror axial symmetry reflector to concentrate sunlight both to gallium arsenide photovoltaic array to be placed along main mirror perimeter and to axial solar cavity, where a modified Rankine cycle with potassium is utilized,
2) flywheels and heat accumulators for a storage of solar energy,
3) combined motor-generating electric machines to be able to overload condition for a time energy exchange cycle;
4) transmitting laser with adaptive optics and with a reflected beam guidance system.

A focusing SPS optics consists of three mirrors: primary, axial selective reflector and periphery hoop-like mirror. The focusing optics is a decoupling filter to be selected an infrared and ultraviolet. The latter is radiated with the help of the optics to space.

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inclination	95'	95'

II. SPS CONVERSION PROCESS LOGIC

In principle, scheme contours of the SPS and ground substation are certainly defined both with an arctic load selection, and with a energy exchange executing within framework of the SPS network itself.

In fact, to meet the consumer heat demands using the heat loss of beam energy conversion to electric power, a distance between reception substation and the heat loads has to be short. This rules out employment of microwave transmission, which requires a large buffer zone of safety. The laser transmission , meeting the mentioned demands, permits also to execute the energy exchange between several SPS.

In it's turn, to operate the laser, which has relatively low temperature of heat waste, the large area for the radiating cooling is required. In general, the use of forced cooling for the lasers has led to a choice of thermal cycle of a solar energy conversion. Moreover, to restrict to a reasonable size of a common radiator area of laser and a thermal cycle, high-temperature Rankine cycle has certainly to be adopted.

The ground substation scheme is certainly defined too with:
- a pulsed operation of laser energy conversion,
- relatively low power level,
- high temperature input, potentially, of the conversion cycle,

and with usage of forced water-cooling for purposes of arctic consumer heating.
This factors have led to a choice of Stirling's thermal cycle.

Application of high-temperature thermal cycle for both the SPS and the ground reception substation permits to initiate them by direct conversion of a concentrated radiation energy.

Laser beam propagation

Space power transmission with a laser beam results in several diffraction divergence of a pencil beam, only. Therefore, an energy loss is absent there. Due to a beam diffraction, the laser transmission would require a 5-m-diam transmitter aperture for a 6-m-diam spot at a 1000 km range (30° zenith angular is assumed for 925 km SPS attitude).

Even taking into account several thermal blooming of the laser beam, small reception aperture would permit to make the SPS substation in the form of transportable variant.
Unlike space conditions, in atmosphere the propagation characteristics depend on various meteorological conditions[6].

Active optics system uses active computer control of transducers to shape the optical surface, allowing correction of mirror distortion, thermal blooming and pointing errors. Beam atmospheric disturbances on the unlink can be greatly ameliorated by cooperative adaptive optics deriving correction signals from reflected beam leading the main beam slightly in the direction of motion through the atmosphere.

Table 2. Transmitting laser characteristics

Output power	2 MW (12)
Working cycle duration	150-300 s
Adaptive reflector:	
diameter	5m
reflectiveness	99.5
Operating temperature	350-500 K
Efficiency	30 %
Wavelength	10.6(2.2)µm
Tracking accuracy	10^{-8} rad
Specific mass	6 kg/kW

III. SPS PERFORMANCE

Independently on the SPS kind, each SPS consists of four components, namely:
1) three-mirror axial symmetry reflector to concentrate sunlight both to gallium arsenide photovoltaic array to be placed along main mirror perimeter and to axial solar cavity, where a modified Rankine cycle with potassium is utilized,
2) flywheels and heat accumulators for a storage of solar energy,
3) combined motor-generating electric machines to be able to overload condition for a time energy exchange cycle;
4) transmitting laser with adaptive optics and with a reflected beam guidance system.

A focusing SPS optics consists of three mirrors: primary, axial selective reflector and periphery hoop-like mirror. The focusing optics is a decoupling filter to be selected an infrared and ultraviolet. The latter is radiated with the help of the optics to space.

Since along an idle section of orbit, converted solar energy is stored up by heat accumulators and flywheels, and along the operating section the flywheels give up its stored-up energy to a combined motor-generating electric machines. They feed a SPS laser, when the SPS travels over the consumer sites and gives to the consumer the energy stored for a 150-sec seance. The flywheels are also, at the same time, with gyroscopic stabilizers of SPS attitude hold in relation to the Sun.

Main principles of SPS operation are following. Sunlight is reflected from a primary mirror and through axial mirror of 15 m in diameter is directed to gallium arsenide photovoltaic area to be placed along a main mirror perimeter. The main mirror of SPS is a scroll-like reflector having rotational symmetry about an axis that is directed to the Sun. Sunlight is too directed from a primary reflector to a concave axial chamber of 15 m diameter through windows into solar cavity.

Within the cavity, the focused sunlight vaporizes liquid potassium and heats the vapor to 2200 K. The 2200 K potassium vapor flows from the cavity to energy-exchanger/binary-cycle power engine.

Table summarizes some of the important characteristics of the suggested SPS of both kinds.

Table 3. SPS characteristics

characteristics	light SPS	heavy SPS
Output to consumers	400 kW	2 MW
Power compression	8	10
Energy capacity	$6*(3*10^6)$kJ	$6*(4*10^7)$kJ
Beam power from SPS	2*2 MW	4*12 MW
Accumulator mass:		
electric	$8*10^3$kg	$15*10^4$kg
heat	$4*10^3$kg	–
Laser mass	$2*(12*10^3)$kg	$4*(50*10^3)$kg
SPS mass	$3*10^5$kg	10^6kg
Diameter of mirror	130 m	450 m
Mirror concentration	200	170
SPS length	70 m	170 m
Radiator area	2.000sq.m	7.000sq.m
Orientation accuracy	15'	10'
Overall efficiency	2 %	3 %(1%)
Specific cost	$8*10^4$\$/kW	$5*10^4$\$/kW

IY. GROUND RECEPTION SUBSTATIONS

The next SPS would beam laser energy by way of adaptive optics to ground reception substation which would collect the laser energy and convert it into electric and thermal energy for consumers placed nearly.

The substation optics would be very similar to those of the laser SPS. SPS azimuth and zenith tracking would be executed by way of a thermovoltaic automatic tracking.

Four major components make up ground substation of the laser SPS:

- reception silvered Gassegrain's type mirror,
- thermophotovoltaic array for forced charge of electric accumulator,
- a heat exchanger for converting laser radiation into useful thermal energy and for charge of heat accumulator,
- helium Stirling's cycle engine and electric generator.

A 6-m-diam receiver mirror would focus and direct the laser beam into a helium heat exchange placed inside a blackbody cavity with 0.1-m-diam opening. The primary receiver mirror would capture the incoming beam and direct it to transfer mirrors which would remove beam jitter. Reradiated losses would be no more than 5% in total.

A hot helium radiates through quartz walls to thermo-photovoltaic array in 2700 to 1100 K temperature range, providing efficiency of the process about 8-10 %.

A temperature range of helium Stirling's cycle operation is 950 to 400 K. Efficiency is about 25 % at 30 kW power. The engine enables short-time overload and many cycles of cold starts.

A thin transparent window covering the laser reception chumber would minimize skin friction and prevent convective flows inside the blackbody cavity and concentrator. The window could be fabricated out of sapphire-like substances. They would make suitable window materials due to their good infrared transmission, high mechanical strength, thermal stability and insensitivity to thermal shock.

Relatively compact heat exchangers can be designed because the laser energy can be focused so as to maintain almost constant, high wall-temperature throughout the entire length of the heat exchanger. Under laser power a reception cavity temperature would reach 2700 K, reducing after helium thermo-photovoltaic conversion to 1100 K for the helium Stirling's cycle.

Table 4. Reception substation

Average power:	80 kW
electric	30 kW
heat	$3*10^5$B.T.U/hr
Concentrator:	
diameter	6m
concentration	4*10
Max. radiat. density	50 kW/sq.sm
Operat.temper.	2700/1100/300 K
Accumulator capacity:	
(T=350 K) electr.	50 KW*hr
(T=960 K) heat	150 kW*hr
Overall efficiency	70 %
(without heat)	35 %
Total mass	1.500 kg
Specific cost	4.000 $/kW

Relatively small reception mirror diameter would permit to make transportable variant of the substation.

During a period of heavy cloud cover the SPS can not transmit energy accumulated for consumer, who needs it. In this case, the coordinate selection of the receptor sites might be executed within framework of the SPS system, when several SPS are met over the north or south pole of the Earth.

The consumers inaccessible by the laser beam change over to the reserve facility (automatic switching of self-contained emergency power). A SPS energy accumulated and not called is transmitted to another SPS, whose current consumer is accessible. The exchange of energy is made near the spatial synchronous points of all SPS, at the same time.

The coordinate selection of receptor sites could reduce the deleterious effects of haze etc. The distribution of power between 150 consumers in full-operative SPS network could provide a energy balance independently of atmosphere conditions.

DISCUSSION

The proposed concept of the SPS may be disputable in some of its details. While the laser SPS has the above-noted advantage over the microwave, microwave can readily penetrate clouds, rain, fog etc. Microwave technology is further developed, and the conversion of microwaves to electricity is more efficient than the conversion of laser radiation to electricity.

No such mechanism could protect a person on the ground who happened to look in the direction of the laser transmitter at the moment of a tracking lock failure. The feedback safety system would shorten the possible exposure time and minimize the possibility of contact.

Technology requirements for creation of the SPS network are not trivial. Most complex component of the laser SPS is high -efficient, megawatt-size, high-coherent laser, which emits in the wavelength range from 2.1 to 2.3µm. Moreover, space based laser has to get high temperature of heat waste rejection by radiation.

In order to feed the mobile consumers by means of the laser SPS reliantly, the lasers are needed with operation at 2.2 µm wavelength, where the atmosphere is practically transparent. Moreover, it is necessary to have gotten the laser gain not less 50 %. In this connection, it should be noted that free-electron generator of coherent radiation with axially symmetric magnetic undulators, are assume, is being developed successfully. FEL development is expected to permit to create reversible beam transmission with operation in 2.2 µm wavelength[7].

CONCLUSION

Main advantages of "donor-accepter" type SPS network are given below:

1. The proposed small-scale SPS network might demonstrate the technical and economic feasibility of the SPS and opens the way for large-scale utilization of a perpetual and inexhaustible source of energy for a post-industrial society. Even existing space vehicles could be used to launch the small laser SPS in the near future.

2. SPS network operation could greatly reduce the amount of fuel that has to be delivered to remote isolated consumers in the arctic regions of USSR, USA and Canada. By selecting the same periodical orbits for all SPS, they back-up each another, securing reliability of the power supply of consumers in case the SPS equipment fails.

3. Due to combined production of electrical and heat energy for consumers in arctic regions, microwave and laser transmission efficiencies are comparable. This will permit to reach economic justification of the laser SPS, that does not influence biota and existing communications.

4. The dependence of laser SPS operation on the weather might be reduced within the framework of the SPS network, by executing coordinative energy exchange between several SPS at orbit points of spatial synchronism. This can be achieved by choosing of periodical polar orbits.

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A5.5 Beam power options for the Moon

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ABSTRACT

At NASA Lewis Research Center, a study was performed to determine the feasibility of providing long term electrical power to the moon's surface by beaming power from satellites. Preliminary reference microwave and laser beam power concepts were developed. The beam power technologies are currently in the laboratory, but much development is needed for a flight system. The beam power systems were shown in some cases to have 1/4 the mass of surface power systems. However, the beam power satellites conceptualized have large space structures that may present complex transportation, deployment, pointing and control issues.

RESUME

Au centre de recherches Lewis de la NASA (NASA Lewis Research Center) une étude a été conduite pour déterminer la faisabilité à long terme d'une alimentation électrique placée à la surface de la lune et alimentée par des faisceaux transportant de la puissance et émis à partir de satellites. Les concepts préliminaires sur la puissance des microondes et des faisceaux laser ont été développés. La technologie de ces faisceaux est actuellement du domaine du laboratoire car beaucoup de développements sont nécessaires pour pouvoir les incorporer dans un satellite. Les systèmes utilisant de tels faisceaux ont montré avoir dans certains cas un quart de la masse de systèmes à alimentation de surface. Cependant les grandes structures des satellites conçues pour ce projet pourraient présenter des problèmes complexes de transport, de déploiement, de pointage et de contrôle.

INTRODUCTION

On the 20th anniversary of man's first landing on the moon, United States' President Bush called for a return to the moon followed by a manned mission to Mars. To accomplish such a bold endeavor, new and innovative technologies will be needed to make these missions affordable. Investigations were undertaken at NASA to identify new technologies and quantify their costs and benefits.

One such innovative technology investigated was beam power as a replacement for/complement to surface power systems. A study was performed to determine the feasibility of providing long term reliable electrical power to the moon and/or Mars surfaces by means of beaming power from satellites. This study was performed at the NASA Lewis Research Center for the Lunar/Mars Exploration Project Office at NASA Johnson Space Center.

A beam power system has several potential advantages over a planetary surface power system. Due to the 336 hour lunar "night", 90 percent of a surface solar power system mass is energy storage. By placing the power source in orbit, and beaming power to the surface, large mass savings can be obtained by greatly reducing or eliminating the eclipse time and the required energy storage mass. Furthermore, lunar surface power systems require propellent masses, approximately equal to the power system itself, to de-orbit from a lunar orbit. Since only a receiver is placed on the surface, most of the de-orbit propellent mass in a beam power system can be eliminated. Orbiting beam power satellites also have an inherent flexibility to power multiple distributed assets on the surface. Finally, there may be some synergistic benefits of integrating a beam power transmitter with a solar or nuclear electric propulsion vehicle. When the vehicle has completed its cargo transportation mission, a "free" source is available for the beam power system.

This paper discusses the approach taken in this study and describes the models used to develop the reference designs including assumptions and groundrules. Results of the major system trades performed, characteristics of the reference designs and a comparison of the beam power masses and the lunar surface power system masses are discussed. Finally, areas of future work are addressed.

STUDY APPROACH

The approach to the study was to identify the beam power subsystems, possible technologies and mission architectures. All support subsystems such as thermal, structure and power management and distribution (PMAD) were included to obtain a realistic end to end system mass. To simplify the analysis, a single lunar base was assumed. Using a spreadsheet model developed for this study, trade-off studies and system mass optimizations were performed. Having gained an understanding for the system trades involved, preliminary reference beam power concepts were developed. The masses and sizes of the reference beam power concepts were then compared with the lunar base power systems developed in the 90 Day Study.

Parametric studies examining beaming to multiple sites and rovers, power beaming options for Mars, and designs using more advanced (far term) technology levels are underway. Operational considerations, such as transportation, deployment and control and technology readiness and development needs are being identified. This paper though only reports on the results to date for a single site using "mid-term" advanced technology for power beaming from satellite(s) to the moon. Many beam power architecture scenarios are possible and results from these future studies may differ from this first scoping effort.

ASSUMPTIONS AND GROUNDRULES

The power profile and system masses from the 90 Day Study were used for references. It was recognized, however, these are point designs used only for scoping purposes, and that beam power may lead to new missions not in the 90 Day Study.

Both solar planar photovoltaic and nuclear reactor power sources for the beam power satellites were considered.

Transmission frequencies ranging from microwave to visible laser region were assumed. The microwave frequencies of interest ranged from 2.45 GHz to 300 GHz. The laser wavelength assumed was 830 nm (360 THz).

The near field approximation used to size the transmitter and receiver areas was:

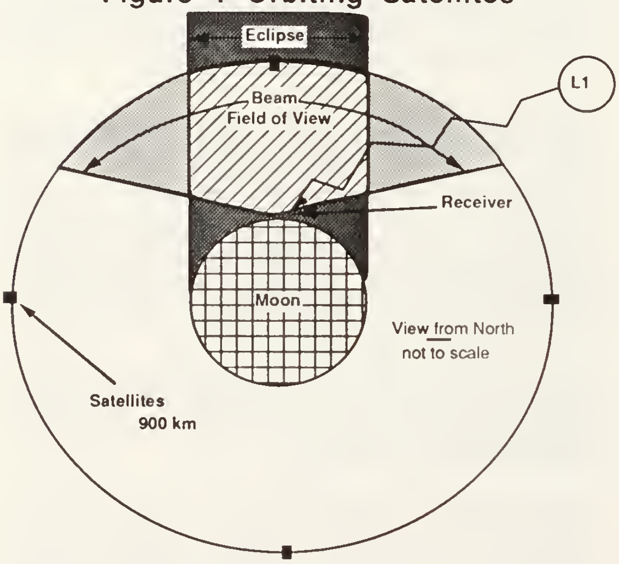
$$P_r/P_t=1-\exp\{-A_tA_r/(LR)^2\} \qquad \text{Equation 1}$$

Where:

R=Separation Distance (m)
L=Wavelength (m)
A_t=Transmitter Area (m^2)
A_r=Receiver Area (m^2)
P_t=Transmitted Power (w)
P_r=Received Power(w)

Figure 1 shows the satellites in a low lunar orbit (LLO) or placed at L1 and the receiver on the surface. When a satellite in LLO is within the assumed 170° field of view for the tracking receiver, energy is beamed to the surface. Four satellites at 900 km or three satellites at 2500 km, provide continuous coverage. If the LLO satellites are in a sufficiently inclined orbit, they experience no eclipse, thereby requiring no energy storage on board the satellite. If the satellites are placed at the libration points L1 or L2, they are in constant sunlight and view of the receiver.

Figure 1 Orbiting Satellites



To de-orbit a 1 kg payload to the surface, 1 kg of propellent is needed; effectively doubling the payload mass in orbit. To obtain an "equivalent surface mass" that could be compared directly to the 90 Day Study surface masses, the orbiting portions of the beam power system are multiplied by 1/2. All total system masses in this report are equivalent surface masses.

Figure 2 is a block diagram of the beam power system. A power source provides power that is conditioned and distributed by the power management and distribution (PMAD). The power is supplied to a transmitter for conversion to electromagnetic energy. From the output of the transmitter, energy can be transmitted directly through space to a receiver on the surface which converts the electromagnetic energy back to electrical energy.

Figure 2 Beam Power Block Diagram

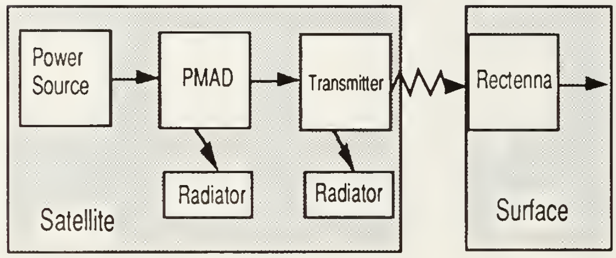


Table I presents the specific masses, conversion efficiencies and operating temperatures for the subsystems. A flight in 2005, was assumed leading to a technology level 3 (system ground demonstration) required for 1990 and level 5 (in-space demonstration) in 1995. The technology required to meet these readiness levels is referred to as "mid-term". The performance characteristics achieved in the laboratory today are listed and projected to the mid term time frames.

1. Demonstrated: These are component level tests in the laboratory. Increased power levels and integration as flight systems may change performance. The laser transmitter has been developed for ground demonstration only, with no weight goal set.

2. Mid Term: The solar array performance is taken from the Advanced Photovoltaic Solar Array (APSA) program using thin GaAs solar cells. PMAD is based on advanced power conditioning and conversion work. The radiators assume advanced aluminum graphite materials.

Gyrotron microwave tubes operating at 35 GHz are assumed for the DC to microwave RF conversion. A rectenna (receiving antenna) which converts the incident RF energy to useful dc electrical energy is based on hybrid construction. The antenna for the microwave system is a metallic mesh reflector. The antenna specific mass includes structure mass to provide stiffness but no structural analysis was performed.

The laser transmitter is an array of electrically pumped laser diodes operating at a wavelength of 830 nm. Single bandgap GaAs solar cells tuned to the 830 nm wavelength convert the laser energy to dc electrical energy.

Table I Technology Performance Characteristics[3-8]

	Demonstrated - 1990			Mid Term - 2005		
	Sp. Mass	Eff.	Temp.	Sp. Mass	Eff.	Temp.
Solar Array	6 kg/kw	20 %	300 K	3 kg/kw	28 %	300 K
PMAD	5 kg/kw	95%	300 K	5 kg/kw	95%	500 K
Radiators	5 kg/m^2	85 %	300 - 500 K	5 kg/m^2	85 %	300 - 500 K
Microwave Transmitter	3 kg/kw 35 GHz	40 %	500 K	3 kg/kw 35 GHz	80%	500 K
Laser Transmitter	50 kg/kw	40 %	300 K	4 kg/kw	38 %	300 K
Rectenna	1.5 kg/m^2	80 %	500 K	1.5 kg/m^2 35 GHz	85 %	500 K
Laser PV Converter	6 kg/kw	20 %	300 K	3 kg/m^2	45 %	300 K
Antenna	1 kg/m^2	100 %	300 K	1 kg/m^2	100 %	300 K

DISCUSSION OF RESULTS

Major Trades

Many system variables can be traded to optimize the beam power system. The trades performed optimize only for total mass. Different reference designs would result if optimizing for areas, volumes and/or cost.

Single vs. Multiple Satellites For a single lunar orbiting satellite, energy storage is required on the surface when the satellite is out of the receiver's field of view. A previous study[1] showed the mass of a single orbiting satellite with surface energy storage exceeds that of a multiple satellite constellation. An exception is to place a single satellite at L1 or L2 where it is in constant view of the receiver.

Satellite Power Source The satellite's orbits are inclined above the eclipse shadow and therefore need no on-board energy storage for a solar powered system. For these power ranges, the solar array specific mass is 3 kg/kw and an unmanned nuclear reactor power system is 17 kg/kw. As a result of its lower specific mass, the solar array power system is the baselined satellite power source.

The inclined orbit requires that the satellite's orbital plane be precessed once per year in order to stay in the sun while in view of the receiver. The propellent mass required for this maneuver has not been calculated.

Frequency and Altitude Effects

Using equation 1, transmitter and receiver areas for 85% transmission efficiency are plotted as a function of altitude at 4 microwave frequencies (2.45, 35, 100 and 300 GHz) and 1 laser frequency (360 THz) in figure 3. As the transmission frequency is increased, the transmitter and receiver sizes decrease leading to a decrease in system mass. In addition, increased transmission frequencies allow higher altitudes resulting in fewer satellites needed for complete coverage (see figure 1).

For the microwave frequency ranges, the antenna/rectenna size is affected greatly as a function of altitude. At 2.45 GHz the transmitter/receiver sizes dominate the system mass. By increasing the frequency to 35 GHz, large mass savings result. At 100 GHz to 300 GHz further mass savings result, however, large magnetic fields (approximately 4 to 10 T) are required for the gyrotrons, These magnetic field levels require that the gyrotron operate either with superconducting magnets, or at harmonics of the cyclotron resonance frequency. Operation at a harmonic frequency reduces the required magnetic field by a factor approximately equal to the harmonic number. However, beyond the second harmonic efficiency rapidly degrades[2]. In addition, for the mid term time frame there is some uncertainty as to the availability of the higher frequency gyrotrons. Therefore, since most mass savings have occurred, and the technology is felt to be available by the mid term dates, 35 GHz was selected as the reference transmission frequency.

Figure 3 Transmitter/Receiver Size vs. Altitude

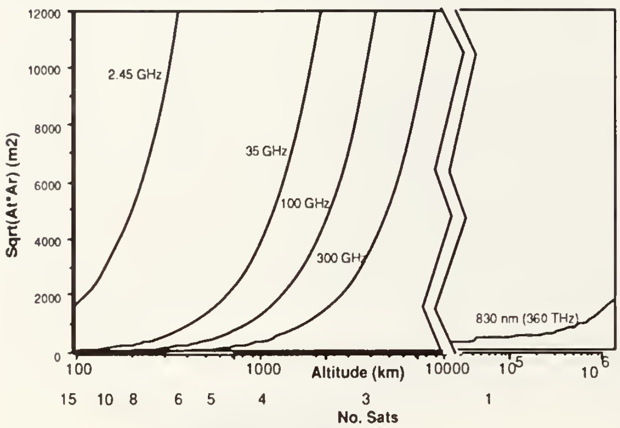
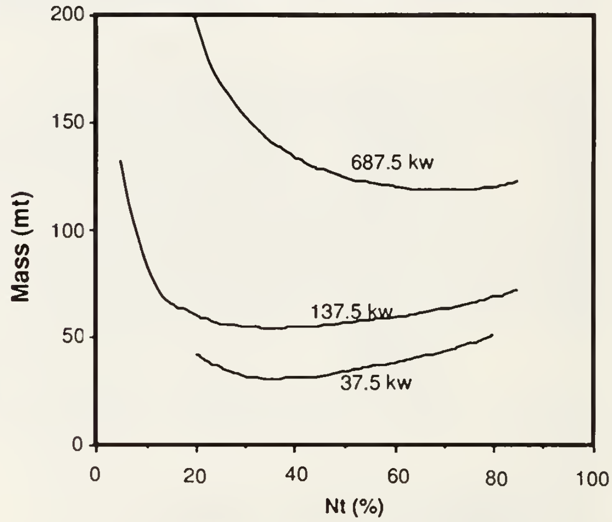


Figure 4 Microwave System Mass vs. N_t



System Mass vs. Transmission Efficiency The size of the transmitter/receiver determines the space transmission efficiency (n_t). Making them larger will increase their mass, but the increased system efficiency will allow a smaller power source. Thus, transmission and power source elements can be traded to minimize system mass.

Microwave beam power system mass vs. nt at various power levels is shown in figure 4. At low power, the system mass is dominated by the transmitter/receiver mass. As power level is increased, maximizing system efficiency becomes more critical due to the source's more dominant role. Indeed, at 37.5 kw, the minimum mass occurs at a n_t of 35%, at 137.5 kw it's at 40% and at 687.5 kw it's at 65%.

It should be noted though, that the minimum is not sharp but allows almost equal system mass over a broad range of n_t. For example, at 137.5 kw, with an nt ranging from 25% to 65%, the system mass varies by only 8%. This indicates that the design parameters are fairly flexible.

Similarly , the laser beam system mass can be optimized for n_t. Due to the high laser transmission frequency, and therefore relatively small transmitter/receiver sizes, the minimum occurs at high transmission efficiency for all power levels of interest.

System Comparisons

Reference Surface Power System In the reference option from the 90 Day Study for the lunar base, 3 Photovoltaic/Regenerative Fuel Cell (PV/RFC) systems provide a total of 75 kw during the day and 37.5 kw at night. The SP-100 reactor with four 50 kw engines is baselined for an additional 100 kw. A reactor coupled to eight 150 kw engines add 550 kw. The reference base power scenarios thus starts with 25 kw day and 12.5 kw lunar night power. They then grow in 4 more steps to 50/25, 75/37.5, 175/137.5, 725/687.5 kw day/night. The reference beam power systems are designed to match as closely as possible this power growth scenario.

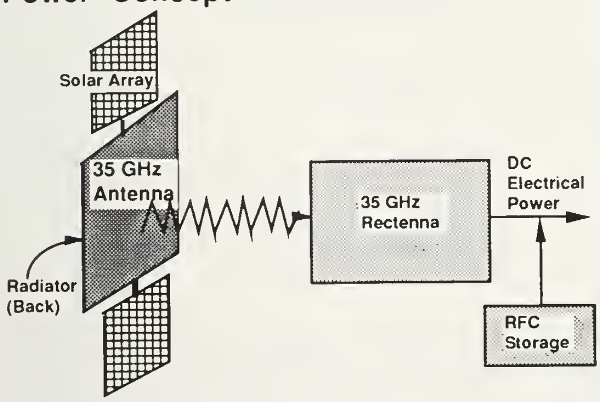
Reference Microwave Beam Power System The microwave beam power system concept is represented in figure 5. The solar arrays are sized as a function of incident solar energy flux (1.35 kw/m^2), system efficiency and power requirements. They are located on the y-axis of the satellite and are gimballed to track the sun.

The 35 GHz gyrotron transmitters are located behind the antenna and radiate RF energy through the planar phased array antenna. The antenna is centered between the solar arrays. The gyrotrons waste heat is rejected at 500 K from radiators located on the rear of the antenna.

The antenna is pointed to direct the microwave energy to the rectenna located on the surface. The rectenna, on a tilted single axis tracker, collects the RF energy and converts it to useful dc electrical energy. Since the power density is less than 1 solar constant (1.35 kw/m^2), direct thermal radiation from the rectenna is assumed.

To allow continuous operation of the system at lower power levels (before a full constellation of satellites is installed) regenerative fuel cell (RFC) storage is used. When the satellite is in view of the receiver, energy is beamed to provide power for the user and to charge the storage. The RFC's provide energy when the satellite is out of view.

Figure 5 Reference Microwave Beam Power Concept



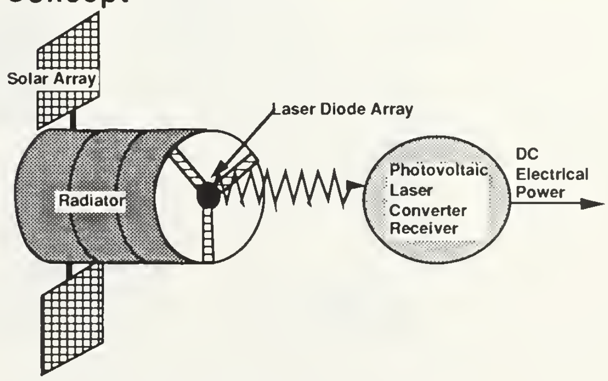
__Reference Laser Beam Power System__ A concept for the reference laser beam power system is shown in figure 6. Solar arrays gimballed on the satellite's y-axis, power a laser transmitter.

Individual laser diodes arranged in an array and cascaded to provide proper phase stability and amplification form the laser transmitter[3]. Operating at 300 K, their waste heat is removed from the rear of the transmitter and transported to a cylindrical radiator for rejection. Although a two sided planar radiator could feasibly reduce this area by half, it was felt to be too large a structure to control. A cylindrical radiator was selected because of its inherently higher stiffness.

The laser energy is directed to a photovoltaic receiver which converts the laser energy to dc electrical power. Due to this relatively large power density (up to 6 Solar Constants), a radiator is required to maintain the photovoltaic solar cells of the receiver at 300K.

Since the laser satellite at L1 is always in view, the only storage necessary is for emergencies and the brief solar eclipses (by the earth).

Figure 6 Reference Laser Beam Power Concept

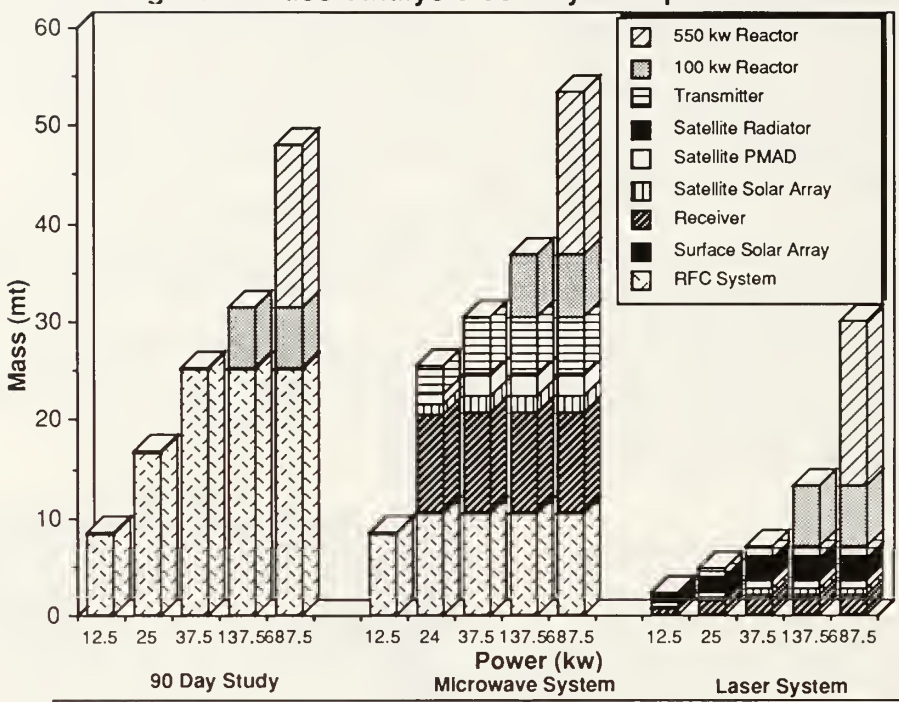


__90 Day Study Comparison__
Total masses and significant areas for microwave and laser beam power systems are compared against the 90 Day Study surface power system in figure 7. The beam power system areas are shown for the largest satellite.

The 90 Day Study surface power system mass of 25.2 mt at 37.5 kw is essentially all RFC's due to the 336 hour eclipse. The 90 Day Study used low pressure gas storage for the RFC reactants. If reactants could be stored in high pressure tanks or liquified to cryogenic temperatures, the mass could possibly be halved. The major areal component is the apron (3789 m^2), an aluminized plastic material that reduces the solar absorptivity of the surface, lowering the effective sink temperature to 222 K, so the nuclear reactor radiators reject heat more efficiently[4].

The microwave system follows the same build up as the 90 Day reference except instead of replicating the PV/RFC plant for the second and third power steps, a microwave beam power system is installed. Initially the single PV/RFC

Figure 7 Mass Analysis-90 Day Comparison



Area m^2

Surface Solar Array	216 m^2	Sat Solar Array	570 m^2	Sat Solar Array	268 m^2
Reactors Radiator	920 m^2	Sat Radiator	16 m^2	Sat Radiator	196 m^2
Apron	3789 m^2	Antenna	4981 m^2	Transmitter	45 m^2
		Rectenna	6642 m^2	Receiver	226 m^2

system placed on the surface delivers 25 kw during the day and 12.5 kw during the lunar night. Two microwave power satellites are then placed in a low lunar orbit to provide the next two power growth steps (ie 25 kw, 37.5 kw). Since the reactants in the RFC's were originally sized to provide energy for the 336 hour lunar surface eclipse, there is more than enough energy storage capability when the satellites are out of view (approximately 1 to 2 hours). Additional electrolyzer and fuel cells, are required however, for the increased power level. Solar arrays are added on the surface for 75 kw of power during the day.

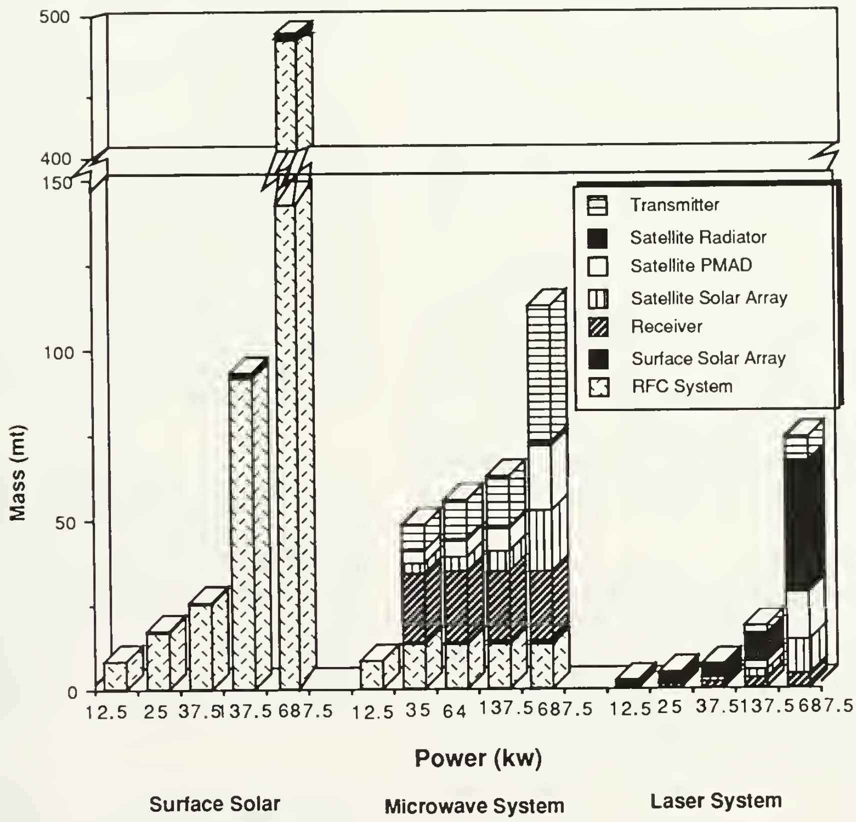
The 21.6 mt mass of the 25 kw microwave system is comparable to the 16.8 mt of the PV/RFC replaced. The transmitter/receiver are the largest mass and areal drivers.

The laser system weighing 7 mt at 37.5 kw, is the least massive of the three power systems. As a result of the low laser operating temperature, the major mass driver is the radiator.

One might expect that since the microwave system transmitter/receiver efficiency is greater than the laser system, that its satellite's solar arrays would be smaller than the laser satellite's. However, the laser solar array area is actually less: 268 m^2 vs. 569 m^2. This is because at 37.5 kw, each microwave satellite must provide the full load and power to charge the RFC's. Each laser satellite provides only 1/3 the power since each is in constant view of the receiver.

At 37.5 kw, the microwave beam power system is complementary to the surface power system and comparable in mass. The laser beam power system replaces the surface power system at approximately 1/3 the mass. However, there are greater uncertainties in the mass numbers associated with the beam power concepts and no station keeping propellent is included in the masses presented. For the case presented, the nuclear reactors were the least mass option for increased power levels.

Figure 8 Mass Analysis-"All-Solar Option"



Area

Surface Solar		Microwave System		Laser System	
Surface Solar Array	$3960 m^2$	Sat Solar Array	$3609\ m^2$	Sat Solar Array	$10132\ m^2$
		Sat Radiator	$510\ m^2$	Sat Radiator	$7409\ m^2$
		Antenna	$6205\ m^2$	Transmitter	$70\ m^2$
		Rectenna	$10343 m^2$	Receiver	$2452\ m^2$

All-Solar Comparison

In case nuclear power can not be used on the surface, an "all-solar option" was investigated. Power levels above 37.5 kw are achieved with additional higher powered beam power satellites. The results were then compared against an all-solar surface power system. The power growth scenario is the same as discussed previously.

Figure 8 shows the microwave and laser beam power systems compared against an all-solar surface system.

For the all-solar surface power system at 687.5 kw, masses (460 mt) and areas (3960 m^2) are extrapolated from the 90 Day Study to the higher power levels.

For the microwave power system, a 25 kw/12.5 kw day/night PV/RFC power system is again placed on the surface. One satellite at a time is used to supply the required power. The first four satellites each provide 162 kw to the rectenna which is converted for the user and RFC recharge. The next four satellites each provide 550 kw to achieve the final 687.5 kw. The total system mass is 113 mt, or 1/4 the mass of an all solar surface power system.

The masses of the subsystems are distributed fairly evenly. At power levels less than 137.5 kw, the transmitter/receivers are the major mass drivers. Greater than 137.5 kw, as expected, the solar arrays and PMAD become mass dominating. The radiator for the largest microwave satellite is relatively small, at 510 m^2, due to the fairly high operating temperature, but the solar array at 3609 m^2, and antenna at 6285 m^2, are very large space structures.

The rectenna although not a significant mass driver, represents a large structure to be placed on the surface.

For the laser case, in the "all-solar option", 5 satellites are positioned at the L1 point to provide the 5 power steps. The first 3 laser satellites each provide 12.5 kw, the fourth adds 100 kw and the fifth adds 550 kw. The laser system mass of 73 mt at 687.5 kw is the smallest of the "all-solar options" presented.

The radiators and solar arrays are dominant mass and area drivers. This is because the laser operating temperature and efficiency are less than the microwave system. As a result, the largest laser satellite requires a 7409 m^2 radiator and 10,132 m^2 solar array.

Technology Evaluation

The technologies needed for the beam power system presented are in the laboratory, but much development would be needed for an assumed 2005 flight. It appears there are no technology "show stoppers" for the beam power systems and much room for performance improvement.

The efficiencies assumed for the beam power technologies are based on small scale developments in the laboratory today. The challenge will be to develop these components into high power flight integrated systems.

In the microwave beam power system, the gyrotron transmitter is existing commercial terrestrial technology, but there is concern as to their lifetime and capability to be steered in a large phased array[2] and a space product will need to be developed. The metallic mesh antenna assumed needs scale-up, development, and demonstration.

The pointing accuracies (0.05 urad), for the higher power laser satellites may be difficult. The lifetime of the laser diodes will need to be increased[3]. Also, in order to accomplish beam steering, large numbers of laser diodes need to be properly phased. Electronic control for phase stability will require high computer processing capability.

In addition to the beam power specific technologies, improvement in other support subsystems are needed. The Advanced Photovoltaic Solar Array power source and the aluminum/graphite radiator work needs continuation for this application. Referring to the table in figure 8, since the satellites can have structures as large as 10,000 m^2, techniques in advanced deployment and control of large space structures need to be demonstrated.

Future Work

This first scoping effort has demonstrated that beam power may be an attractive mass option for powering a single lunar site. As a result, further detailed beam power study work is being pursued in order to quantify the mass and cost benefits for other architecture scenarios, "far term" technology applications and SEI synergisms.

An architecture that needs investigation is power beaming to multiple surface sites including rovers and science platforms. The advantage is that once a power system exists for a main site, additional sites need only a receiver that can be easily stowed and deployed. Beam power for Mars as well as the moon needs investigation. An alternate scenario that should be explored is laser beaming from earth to the moon.

For missions beyond 2005, more advanced technologies may be available to lower system mass. A light weight thin film integrated design marrying solid state microwave transmitter directly with the solar cells could eliminate the separate PMAD and antenna and allow the whole array area to be used as the antenna aperture. Alternatively, if high efficiency, high frequency (> 100 GHz) DC to RF converters can be developed, significant reductions in mass will result from smaller antennas and rectennas. Similarly, improvements in laser efficiency and/or lighter weight radiators would help the laser systems.

A Nuclear or Solar Electric Propulsion (N/SEP) vehicle can potentially provide a "free" source for the beam power system. This synergistic benefit could result in lower mass and cost for a beam power system.

Although the masses of a beam power system under certain mission and technology assumptions is favorable, operational issues will need to be addressed. Specifically, technology for on-orbit deployment, pointing and control of the large satellite structures needs to be identified, developed, and costed. The packaging and integration with launch vehicles needs investigation.

Conclusions

The dominant mass for a lunar surface solar power system is energy storage. By beaming power from orbiting satellites, the energy storage can be greatly reduced or eliminated. Since the beam power source stays in orbit, further mass savings can be realized by eliminating the need for de-orbiting propellents (except for the surface receivers) .

The mass savings are a strong function of mission scenario and power level. At low power (10s of kw) the microwave beam power system is comparable in mass to a surface solar system. Laser systems are 1/4 to 1/3 the mass of surface power systems. At higher power, surface nuclear reactors are the lowest mass option. But, if nuclear power is "ruled out" for the moon, beam power presents an attractive mass option.

Although the masses of a beam power system can be as little as 1/4 the mass of an all solar surface power system, extremely large space structures are required. These present complex transportation, deployment, pointing, control and stability issues. The dominant microwave satellite structure is the large antenna resulting from the relatively low 35 GHz transmission frequency. For the laser satellite, the dominant structures are the solar arrays and radiators resulting from the lower efficiency and operating temperature of the laser diode transmitters.

The beam power concepts presented are based on a narrowly constrained architecture scenario and technologies extrapolated to an assumed 2005 mission. Additional beam power scenarios and/or use of more advanced technologies may result in further SEI mission benefits and increased mass savings. Because of this, beam power system are being studied further.

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SPS 91

A6.1 Magnetically inflatable SPS with energy storage capability

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Abstract

A new approach to Superconductive Magnetic Energy Storage (SMES) for Solar Power Satellite (SPS) with inherent rigidity is introduced in this paper. The rigidity of this SMES originating from the electromagnetic forces within it, can eliminate the need for mechanical building blocks for support structure. This force can also be used for the deployment of the system in space. In addition, the storage capability of the system allows its use in low earth orbit (LEO) which reduces the launching and transmission costs. The paper also discusses the basic design and the operation of the proposed SPS system.

I. Introduction

Superconductive Magnetic Energy Storage (SMES) has been studied for ground based electrical power systems for many years [1,2,3]. The application of the same concept to space power systems has also been suggested by a few workers [4,5]. In this paper we will introduce the concept of magnetically inflated (self supporting) SMES to the solar power satellite (SPS). Figure 1 shows a schematic diagram of the system. The rigidity of our magnetically inflatable solar power satellite (MISPS) originates from the inherent electromagnetic forces of a SMES ring. This can eliminate the need for mechanical building blocks to support the SPS structure. Thus, the weight and volume of the materials that are needed to be launched can be reduced. Furthermore, the SMES part of MISPS system can be launched in a collapsed form. Once in orbit, it can be "magnetically inflated" by a small source, such as a pilot solar photovoltaic or nuclear-electric energy source.

In addition to the self structural support, the MISPS concept will provide bulk energy storage capability to the SPS system. This will have even more profound impact on its design and operation. The MISPS system can be built in small units and placed in low earth orbit (LEO). The launching costs to LEO are significantly lower than those of geosynchronous earth orbit (GEO), which are envisioned for the SPS. Furthermore, LEO will also reduce the microwave power transmission system size and complexity. Another advantage of a MISPS in LEO includes the possibility of multiple earth receiving stations from one or more orbiting systems.

However, a MISPS in LEO will be in the line of sight of a receiving earth station only intermittently. Thus, the transmission from each MISPS unit is by periodic long pulses, while it is in line of sight. This difficulty can be alleviated by installing a SMES in the receiving station as well. Thus, the SMES system will act as a buffer between the intermitant source and independently varying electrical load at the ground station. Similarly, the SMES in MISPS will balance the variations of energy reception and transmission in each orbit.

The details of MISPS orbital behavior and its general design characteristics are the subject of the remainder of this paper.

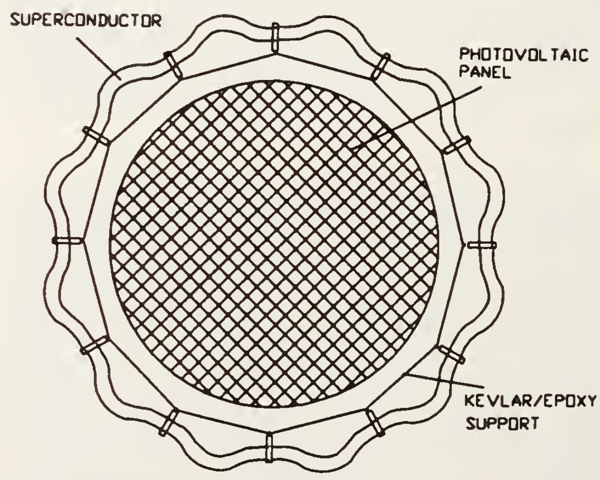

Figure 1 Schematic Diagram of the Magnetically Inflated Solar Power Satellite

II. MISPS in LEO

Assuming an approximate equatorial orbital period of $T \cong 100\text{min}$, the line of sight fraction of the orbit, from a point on the equator, is ideally about 10%. Assuming power transmission during this segment of the orbit, the power transmission duration in terms of the period is

$$t_t = 0.1T. \tag{1}$$

For this orbit the dark eclipsed segment in terms of the period is

$$t_D \cong 0.39T. \qquad (2)$$

Therefore the fraction of the period in which the satellite can receive solar energy will be

$$\begin{aligned} t_r &= (1 - 0.39)T \\ &= 0.61T \end{aligned} \qquad (3)$$

When the SPS is in operational equilibrium the total energy received must be equal to the total energy transmitted per period. This implies that

$$P_t t_t = P_r t_r \qquad (4)$$

where P_t is the microwave transmission power and P_r is the solar electrical received power. Substituting in terms of the orbital period,

$$P_t \cdot (0.1) = P_r \cdot (0.61) \qquad (5)$$

$$P_t = 6.1 P_r$$

The power profile for one orbital period under the above scenario is shown in Fig. 2.

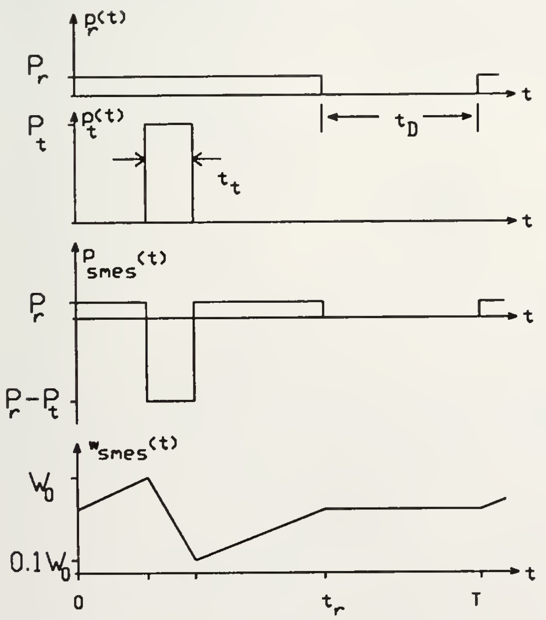

Figure 2 The Power and Energy Profiles of MISPS for One Orbital Period

The SMES power, P_{SMES}, is the balance between the received and transmitted power at any instant.

For structural integrity of the magnetically inflated SMES, we will assume a magnet current variation of from 100% to 33% of the nominal SMES current, I_o. The lowest SMES current (0.33 I_o) will occur at the end of the transmission period, t_t. The highest SMES current (I_o) will occur at the beginning of the transmission period. This implies that the energy content of the SMES is a maximum of W_o at the beginning of the transmission and $0.1W_o$ at the end of transmission.

The energy rating of the SMES can be found from the above discussion as follows.

$$0.9W_o = (P_t - P_r)t_t \qquad (6)$$

Therefore,

$$W_o = \frac{1}{0.9}(P_t - P_r)t_t, \qquad (7)$$

or in terms of photovoltaic power rating and orbital period:

$$W_o = 0.57 P_r T \qquad (8)$$

Nonequatorial Orbits

The above calculations are for an equatorial orbit and receiving station. For a nonequatorial orbit and receiving station the MISP's observation angle from the ground station will not be the same for each pass, due to the rotation of earth. This effects the power transmission time t_t. Furthermore, the solar energy receiving time, t_r, can increase from 0.61T to T, as the orbit tends toward the polar. Conversely, the eclipse time, t_D, changes from 0.39T to 0. For example, in the polar orbit the MISPS can receive sunlight all the time if the orbital plane is normal to the sun rays and the receiving time, t_r will be equal to T.

The number of passes per day are also effected by nonequatorial systems. For example, in our example of the equatorial orbit and receiving station, about 14 passes per day occur. The number of passes drop to about 4 per day if the MISPS is in polar orbit. For a typical example of a 60^o orbital angle of inclination (the angle between the equatorial plane and the orbital plane), and an earth station, having a $+30^o$ latitude, the number of passes per day is about 8.

Seasonal changes and other perturbations, such as gravitational, geomagnetic and solar pressure also effect the orbit and the eclipse time. These effects need to be accounted for and corrected by additional work which is outside the scope of this paper. The variations due to nonequatorial orbit and receiving stations also effect the energy storage and power transmission ratings of the MISPS. However, multiple satellite and earth stations will help even out the duty cycles of transmission and storage.

III. Design of the MISPS

The magnetically inflated loop serves two functions: 1) It provides structural support; 2) It stores energy. Therefore energy storage capacity and force calculations are necessary for design. To simplify the calculations an ideal circular single conductor loop will be assumed for the MISPS (Fig. 3).

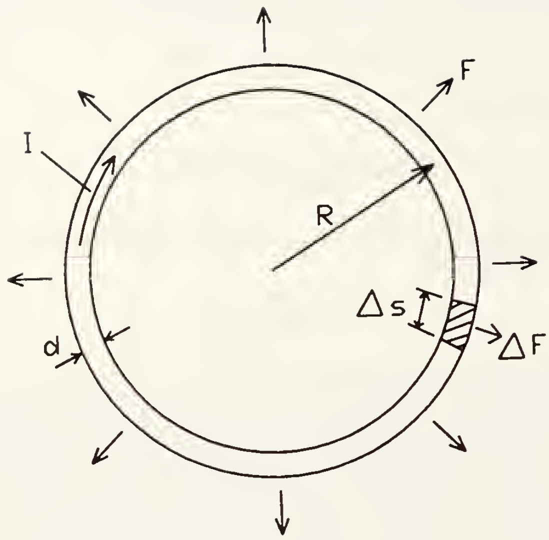

Figure 3 Circular Approximation of the MISPS Coil

The photovoltaic system and microwave antenna will be placed inside the loop as shown in Fig. 1. Therefore to find the loop radius, the area of photovoltaic system (S) has to be calculated first. Assuming an electrical output power of $100W/m^2$ for P.V. system, its surface area is

$$S = \frac{P_r}{100}, \quad m^2 \tag{9}$$

If a disk P.V. panel is used, its radius will be

$$R_{pv} = \sqrt{\frac{P_r}{100\pi}}, \quad m. \tag{10}$$

The SMES loop radius, R in meter, will have to be greater than R_{pv} in our design.

The loop inductance can be approximated as follows where d in the conductor cross sectional diameter in m.

$$L = 4\pi 10^{-7} R.\ ln(\frac{2R}{d}), \quad H \tag{11}$$

The above expression is derived under the assumption of a very low aspect ratio coil [6].

The radial force, F, can be calculated from the energy conservation principle [7].

$$F = \frac{dW}{dR}, \quad N \tag{12}$$

This force is the total force around the loop. The radial force on the loop is

$$F_R = \frac{\triangle F}{\triangle_S} = \frac{F}{2\pi R}, \quad N \tag{13}$$

From (10), (11), (12) and (13) we get,

$$F_{R,MAX} = \frac{2 \times 10^{-7} I_o^2}{R} ln(\frac{2R}{d} + 1). \tag{14}$$

If the maximum current density of the superconductor is J_c and its cross section is A, the maximum loop current will be

$$I_o = A.J_c = \frac{\pi d^2}{4} J_c, \quad A \tag{15}$$

Assuming a maximum energy storage of W_o, the maximum loop current will be

$$I_o = \sqrt{\frac{2W_o}{L}}, \quad A \tag{16}$$

From (13), (14) and (15) we will get

$$d^4 ln(\frac{2R}{d}) = 2.58 \times 10^6 \frac{W_o}{J_c^2} \tag{17}$$

This is a useful design equation for finding the total cross sectional diameter of the superconductor and the required current density when W_o and R are given.

100 MW MISPS

An earth orbiting MISPS having a period of 100 minutes was assumed. The power transfer duration, t_t, the dark eclipsed segment, t_o, and the period during which the satellite can receive solar power, t_r, are as follows

$$\begin{aligned} t_t &= 10\text{min} \\ t_o &= 39\text{min} \\ t_r &= 61\text{min} \end{aligned}$$

From (4) the solar electric power is

$$\begin{aligned} P_r &= P_t \cdot \frac{t_t}{t_r} \\ &= 16.4MW. \end{aligned}$$

From (7) the maximum energy to be stored is

$$\begin{aligned} W_o &= \frac{1}{0.9}(100 - 16.4) \times 0.167 \\ &= 15.5MWh. \end{aligned}$$

Using (8) the required photovoltaic area is

$$S = \frac{16.4 \times 10^6}{100} = 16.4 \times 10^5 m^2.$$

This is the area of a disk with 228 m radius. The superconductive loop around this circular panel will be far enough away to have a negligable magnetic field effect. The superconductive loop radius is chosen to be $R = 250m$. For a $J_c = 500A/mm^2$ and $W_o = 15.5MWh$ the loop conductor cross section diameter can be obtained from (17) to be $d = 13cm$. From (16) we find,

$$I_o = 6.6 \times 10^6 A$$

This current is for single turn superconductive loop. In order to impose a reasonable current e.g., 1 kA, on the power converter, the loop can be made of 6600 turns.

From (13) the radial force is found:

$$F_R = 30.5\ ton/m.$$

The above force is an approximation for a circular SMES. A practical design would utilize a rippled loop configuration as shown in Fig. 1. The loop is supported by a polygon of Kevlar under tension. The details of this basic design will determine the exact tensile forces on the Kevlar and superconducting components.

Assuming a superconductor density of $3gr/cm^3$, the total weight of the conductor will be

$$M_{sc} = 63\ tons$$

The 100 MWh MISPS specifications are summarized in Table I.

Table I. 100 MW MISPS Specs

Orbital period	100 min
Solar Panel Radius	228 m.
Superconducting loop radius	250 m.
Maximum Stored Energy	15.5 MWh
Radial Force (max)	30.5 ton/m
Total superconduting loop cross section	$133cm^2$
Max superconducting loop current density	$500A/mm^2$
Number of turns of the coil	6600 turns
Coil current	1 kA
Conductor Weight	63,000 kg

V. Comparison of SPS in GEO vs. LEO

One major difficulty with SPS in geosynchronous is the large spot on earth which is illuminated by the microwave beam. This area must be mostly covered by the receiving rectenna array if the power transmission efficiency is to be high. Thus the area of the rectenna array is fixed by the distance (24000 miles for GEO) and the frequency of the microwave beam (2.45 GHz in the baseline design). Efficient use of the rectenna array then requires an energy density in the beam such that the rectenna elements are loaded up to their ratings. To fit an economically viable design into the above framework, a baseline design of 5000 MW has been suggested. Of course, this also requires a correspondingly large photovoltaic array and transmitting capability on the SPS. Hence, the weight of the SPS which must be placed in geosynchronous orbit is large. Accordingly, the cost of a single SPS is very high and incremented development is really not possible.

However, the advantage of the GEO SPS is the almost 100% utilization of both the transmitting and receiving elements. This follows because the photovoltaic (PV) array in orbit is almost always illuminated by the sun. Considering the LEO SPS, proposed in this paper, the PV array is illuminated only about 2/3 of the time, thereby diminishing the utilization factor of the PV array. Furthermore, the rectenna site on earth is only within view of the orbiting SPS for a small fraction of the orbit. The above window is further constricted if the rectenna and the SPS orbit are not on the equatorial plane. Therefore, the utilization factor of the rectenna site will be very low if only one SPS is in orbit. Clearly the utilization factor of a rectenna site will improve it more than one SPS is in orbit. Furthermore, if more than one rectenna site exists on earth, the SMES capacity of the SPS can be reduced since the collected energy will be transmitted more frequently.

The spot on earth illuminated by a microwave beam of a given frequency with lower orbits; e.g., 2.45 GHz, will be proportionately reduced as will be seen in the following section. Thus, using the argument given earlier, capability, and hence weight and cost, of a LEO SPS will be much less than a GEO SPS. This would reduce the financial (and political) cost of a first SPS launch and would, it seems, facilitate an incremental development of a scheme with multiple SPS in orbit and multiple rectenna sites around the earth.

The Impact of Orbital Radius on the Antenna

The size of sending and receiving antennas are dramatically reduced by the concept of magnetically inflated solar power satellite (MISPS) in LEO, as compared to GEO. This is evident from the following. At a given frequency, the efficiency, η, of a microwave transmission is approximately given by

$$\eta \leq k\frac{AsAr}{D^2},$$

where A_s and A_r are the sending and receiving antenna areas, D is the separation distance and k is a constant [9]. For example, from GEO to a LEO of 480 miles, the distance is reduced by a factor of 46. Therefore, both sending and receiving antennae areas will be reduced by about 7 times. However, the line of site fraction of the orbit for a point on the ground will also be substantially reduced; e.g. by a factor of 3. Therefore, for the same amount of energy, transmission has to be trippled. This will also modify the antenna sizes to some extent.

IV. Superconductor, Cryogenic and Support Material

$NbTi$ can be chosen for the superconductor material. It has a critical current density, J_c, greater than 3000A/mm^2 [8]. In our design J_c is assumed 500A mm^2 for quench protection.

The cryogenic system will use liquid He to keep $NbTi$ below $4K^o$. The helium can be placed between the superconductor and an aluminum vacuum jacket.

The superconductor is subject to a high tensile force in normal operation. $NbTi$ with copper

or aluminum stabilizer can not withstand this force. Therefore Kevlar/epoxy tensile supports must be used. This material has excellent tensile strength and fatigue properties [4].

V. Conclusions

In this paper we have introduced the concept of superconductive magnetic energy storage to the solar power satellite. The potential benefits of this concept are manifold, as described in the paper. All of these benefits stem from the two basic characteristics of MISPS which are energy storage and structural self support.

Perhaps the most important benefit of the MISPS concept is its economic flexibility. The system can be composed from several smaller orbiting units. The number of these units can be gradually expanded from one to the minimum number needed to have one MISPS in the line of sight of an earth station at all times. This evolutionary expansion can be financed by a bootstrapping strategy, where part of the payback of the installed system is reinvested in the next MISPS unit. This economic strategy can be enhanced by selling power to several isolated earth receiving power stations.

Several disadvantages can also be envisioned for the MISPS concept, perhaps the most prominent among them is the application of an unproven SMES technology and its associated complexities. Furthermore, the mechanical forces resulting from the interaction of the SMES magnetic dipole and the earth's magnetic field can destabilize the MISPS. However, spin stabilization and active timing should provide adequate means of correcting this problem.

A significant amount of basic research remains to be done on the MISPS concept. Among these are conceptual design of the magnet and its tensile support structure, the cryogenic and other support requirements of the SMES and the power electronics required for electrical energy conversion on both receiving and transmission sides of the orbiting MISPS.

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RESUME

Une nouvelle approche de SMES pour centrale solaire spatiale ayant une rigidité mécanique intrinsèque est présentée dans cette communication. La rigidité de ce SMES engendrée par les forces électromagnétiques internes mises en oeuvre permet d'éviter une structure mécanique rigide. Ces forces permettent également le déploiement du système dans l'espace. Ce système de stockage d'énergie permet une utilisation en LEO avec des coups réduits de lancement et de transmission. Cette communication présente les règles de base de dimensionnement et de fonctionnement d'un tel système.

A6.2 Application of the concept of inflatable and rigidifiable structures to large space power stations

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SUMMARY

The inflatable and rigidifiable space structures allow henforth to realize economically, because without cosmonaut,large solar power satellite.
The paper presents an experimental solar power satellite that will allow to qualify the different SPS concepts and to prepare a large exploitation.

RESUME

Grâce aux structures gonflables rigidifiables dans l'espace il est désormais possible de réaliser très économiquement, car sans intervention de cosmonaute, des grandes centrales solaires spatiales.
L'étude présente une centrale expérimentale qui permettra de qualifier les divers aspects du concept SPS et de préparer une première phase d'exploitation.

TABLE OF CONTENTS

1- MAIN OBJECTIVES

The principal objective is the design and construction of an experimental space power station compatible with to-day's techniques and technology.
This space station will allow to certify the specific sub-systems: the subsystem that will collect the solar energy, the solar panels, the sub-system of transmission, the receiving ground station.

This experimental space power station is very economical (about the price of most usual large satellites) because its deployment in space is entirely automatic and does not requires a man mission. It can be launched by an Ariane 5 rocket.

The other main objectives are the following:
Certification of the technology of large space stations with automatic deployment, that will be necessary for future operational SPS.
Certification of SPS systems with non-geostationary satellites.

2- PROPOSED CONCEPTS

GENERAL ARCHITECTURE

The main elements of the station are the following (see figure 1).

A) A large parabolic reflector (2) that concentrate the solar energy at the focus.
B) A conical system collecting the solar energy about the focus with solar panels on the outer(5) and inner (6) faces.
C) A main bus(A) that governs the different functions of the station and is placed in the shadow of the conical collecting system.
D) A secondary bus (B) at the back of the station with the communication antennas and with the system of transmission of energy.

Dimensions of the station after deployment:
diameter of the large parabolic reflector: 50m,
width: 35m.

ORBIT

The dimensions of the antennas of the transmitting and receiving systems increase with the distance between the satellite and the ground receiving stations. They also increase with the wavelength of the radioelectric waves.

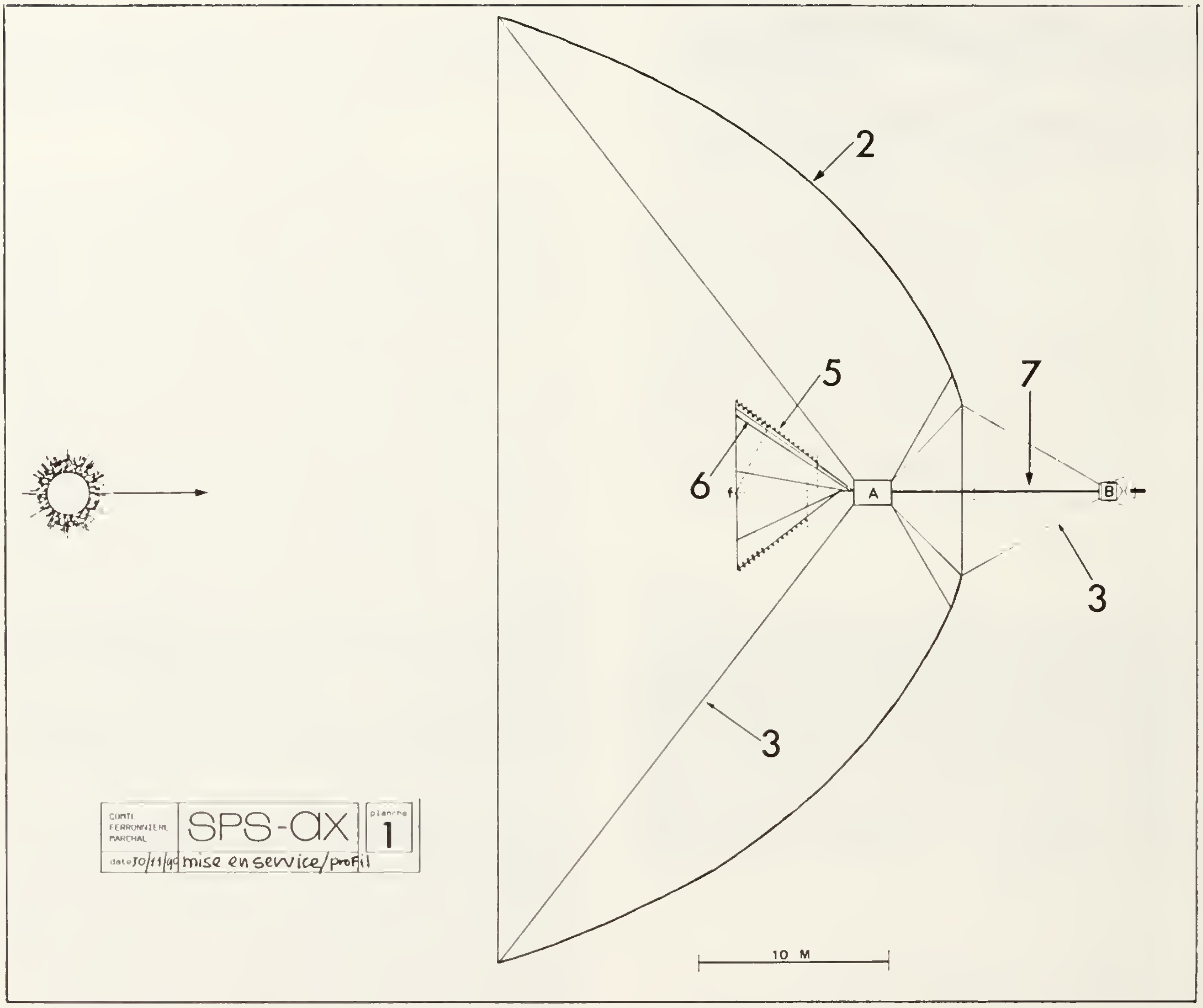
For transmitting antennas of a few meters it is necessary to use micrometric wavelengths (laser) and short transmitting distances.

A systematic comparison of advantages and drawbacks of the different orbits is presented in section 4.
This comparison leads to the two followings cases:

a) For the experimental studies an excellent orbit is the heliosynchronous circular orbit "always in the Sun" at an altitude of about 2000km and an inclination of about 105° (launching at Kourou near 18h towards North/North-West).
b) Later for the industrial exploitation it will be preferable to use a circular equatorial orbit at an altitude of about 8800km (period 5h 10mn).

TECHNOLOGICAL CONCEPTS

The technologies used for this project of experimental station have already been studied by several organisms.



A) Arsat Association and Zodiac Company: studies and researches on large, inflatable and rigidifiable space structures.

General architecture, deployment by inflation, rigidification by polymerisation of a special epoxyd resin, stabilisation and control of orientation by the magnetic torques on large electric loops.

B) European Space Agency and Contraves A.G. : studies and researches on large deployable space antennas, with a rigidification in space by the polymerisation of an epoxid resin under the influence of solar U-V.

Let us describe now the succession of utilized technologies.

I- LAUNCHING INTO ORBIT (Figure 2)

A large cylinder, compatible with Ariane 5 (diameter 4.5m, length 12m, mass about 5 tons) contains all the elements of the future space power station and an apogee motor.

The elements can be classified into two main categories:

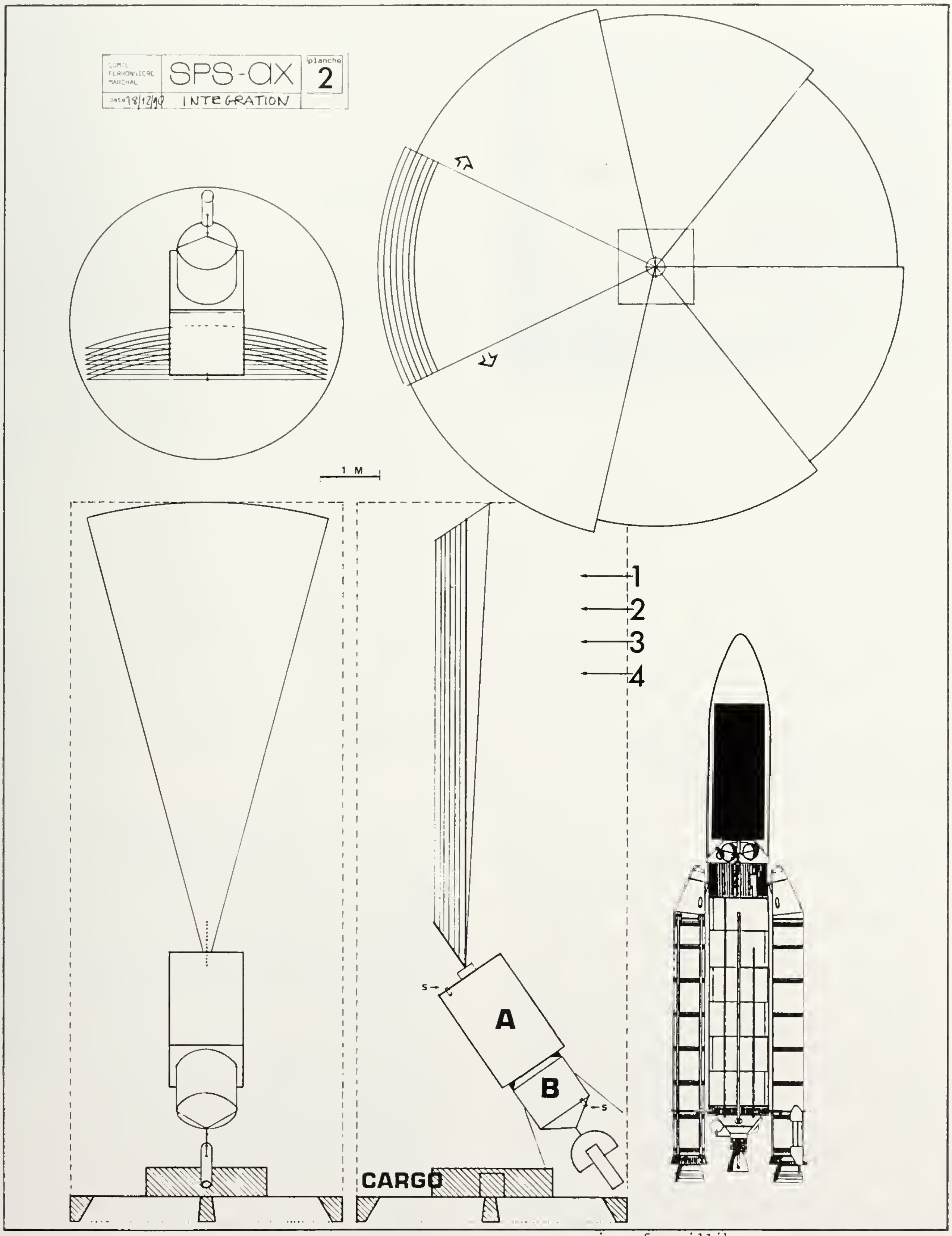
A) The rigid elements.
The main bus (A) that carries the seven conical and mobile elements carrying the solar panels on their two faces.
The secondary bus (B) carrying the antennas and the orientable platform on which is fixed the laser system transmitting the collected energy to the ground.
At launch the two buses are adjoining and the rigid elements fill the main part of the cylindrical cargo (Figure 2).

B) The non-rigid elements.
These supple elements will, after deployment and rigidification, constitute the general architecture of the station. Their composition will be analysed later.
These supple elements are placed according to a suitable folding system about the rigid elements.
A suitable protection is used at the interface.

The separation between the cylindrical cargo and the third stage of the Ariane launcher as well as the ignition of the apogee motor are automatic and use well-tried techniques.

II- DEPLOYMENT AND RIGIDIFICATION (Figure 3)

The large parabolic reflector is deployed by inflation of a large balloon that contains the rigid elements.
This balloon has the following parts:
A skin in reinforced and metalized plastic (2) (supple composite).
A large spherical and transparent cap and a smaller one in non reinforced plastic (1).
Several electric loops along the largest perimeters of the structure (0).
Several electric wires around the two spherical caps and along several diameters (4).



Several cables and shrouds (3) that, after deployment, will fixed the two buses along the main axis (figures 1 and 3).

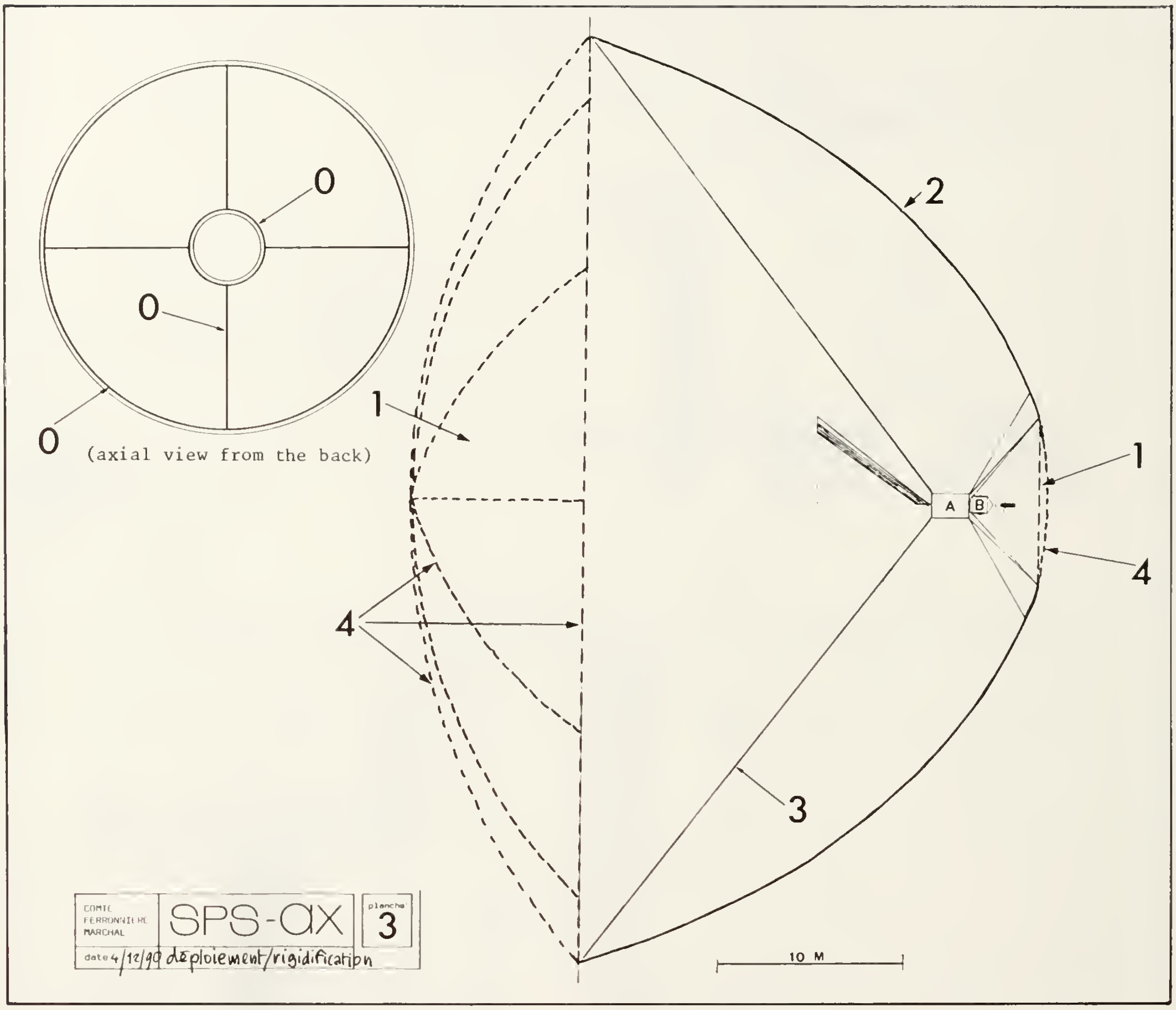
The sequence of deployment is the following.

A) Aperture of the cylindrical cargo and ejection of the two half-cylinders.

B) Inflation of the structure by vaporisation of a liquid contained in the main bus. The resulting pressure is a few millibars.

C) Rotation of the structure, with the electric loops and the electromagnetic torque given by the local electromagnetic field. This slow rotation (period about 30mn) is about an axis normal to this of the paraboloid and will present to the solar U-V all parts of the structure.

D) Polymerisation of the structure of the large reflector.



The technique of the composite pre-polymerised materials uses both the effects of the heat and the catalytic effects of the solar U-V on an epoxid resin lying along the reinforcement of the external structure.
This reaction will require about two days.

E) Expulsion of the remaining gas.
After the polymerisation the reflector is rigidified and the expulsion of the gas of the balloon is necessary (if not the impact of a micrometeorit could lead to disorderly motions).
This expulsion is done simultaneously at the two opposite ends of the axis of the reflector.

F) Ejection of the two spherical caps.
The mission of the two caps is to allow the inflation of the balloon and the rigidification of the structure.
Their ejection requires the three following phases.
F.1. Rotation of the structure about the axis of the paraboloid (period 6 to 10mn).
This rotation is of course obtained with the electric loops and the torque given by the electromagnetic field.
F.2. Cutting out of the spindles of the two caps (fusion of the plastic materials along the diametral wires)(4).
F.3. Cutting out of the perimeters of the two caps that are then ejcted by the centrifugal forces.

III- SETTING IN OPERATIONAL CONFIGURATION, THE FINAL MANEUVERS (Figure 1)

The final maneuvers set the different rigid elements.

A) Deployment of the two buses.
The long pole (7) that joins the two buses is pneumatically deployed as is mechanically bolted. The rigidity is insured by several cables and shrouds (3).
The secondary bus, that carry the orientable platform of the laser transmission system is at the back of the reflector in a good position for the transmissions to the ground.

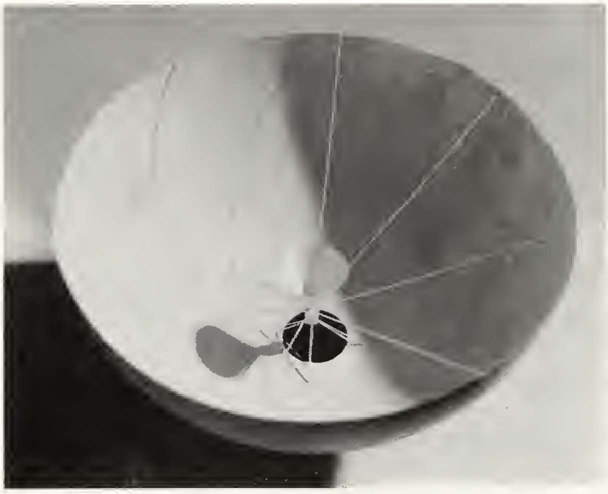
B) Deployment of the energy collecting system.
The energy collecting system is composed of solar panels placed inside and outside the collecting cone. This cone is in seven parts linked to the central axis of the main bus A (see figures 2 and 3).
The deployment of the seven parts is symmetrical (rotations about the central axis) and in the final position the focus of the large collector is at the intersection of the central axis and the base plane of the cone (see figure 1).

3- DIMENSIONING: GENERAL PRINCIPLES

The experimental solar power station presented in this study use the following principles.

The main axis of the paraboloid is continuously pointed towards the Sun and the attitude is permanently controled and, if necessary, corrected with the help of the electric loops and the corresponding magnetic torque.
The laser transmitter and the antennas are pointed towards the ground station, they are on the orientable platform at the back of the secondary bus (B).

In the industrial version, it will be possible to transmit the electric energy to several successive ground stations when the satellite travels along its orbit (Figure 4).



GENERAL CHARACTERISTICS OF THE STATION

The main constraints are of course the capacity of the Ariane 5 launcher, the performance of the solar panels (efficiency, resistance to heat) and these of the laser transmitter (large power).

The dimensioning of the laser energy transmitting system is a difficult question that we will study accurately with concerned specialists.

Section of the reflector	1900m2
Accuracy of the orientation of the laser beam......	30"
Received power....................................	2,6 MW
Efficiency of the reflector......................	90%
Surface of the solar panels	140m2
Amplification coefficient (on the solar panels)....	$\frac{1900}{140} = 14$
Density of power on the solar panels..............	17kW/m2
Expected efficiency of the solar panels	About 20%
Transmitted electric power	About 500 kW
Maximum temperature of solar panels	320°C
Density of radiated thermical energy	About 13,5kW/m2

All these characteristics will of course be stated more precisely in the next phase of the study of this experimental station according to the here described general principle and to the characteristics of the energy transmitting system.

4- TOWARDS AN OPERATIONAL SYSTEM OF EXPLOITATION

STUDY AND SELECTION OF ORBITS

The choice of a good orbit is one of the main elements of the efficiency of a space power station. This choice influences the distances of transmissions, their durations, periodicities and intervals it influences also the danger of radiations and space debris, the proportion of time passed into the Earth shadow and thus lost for the production of solar energy...

The study of an experimental space station is very different from that of the production of large quantities of space solar energy. In the first case we must study mainly the production of energy and the quality of its transmission towards Earth, in the second case the economical factors become essential: large production, maximum efficiency, smallest price, smallest risk of troubles and interruptions.

ANTENNAS AND WAVELENGTHS

The transmission of energy depends very much of the chosen orbit and of its distance to the Earth. An antenna with the diameter D sends at the distance L a main beam with the diameter Δ related to the wavelength λ and to D and L by:

$$D\Delta = 2.44\ L\lambda$$

In order to collect the main part of the transmitted energy the receiving antenna must have a diameter of the order of Δ and this shows the importance of the product $L\lambda$ and the interest of laser transmission with short wavelengts λ .

In the classical projects the wavelength λ is a microwave of 10 to 15 cm (for instance 12.2cm for the often consired frequency of 2450 MHz) and the distance L is the geostationary distance(35 800km). The product $D\Delta$ is then of the order of 10km2 which requires for instance D= 1km and Δ = 10km that is immediately gigantic.

However it is possible to choose L and λ smaller with an orbit lower than the geostationary orbit and with infra-red wavelengths.

For instance, with L= 8 800km and with λ =9.11 μm (CO2 laser with oxygen 18) we obtain

$$D\Delta = 2.44\ L\lambda = 196\text{m2}$$

That is 50 000 times less than in the classical projects...
In these conditions with several laser-transmitters on a 100m structure it is possible to use only a 20m receiving antenna that can be placed almost anywhere and even at the top of a mountain.
The laser transmission has, of course, its own drawbacks, the efficiency is small and the clouds absorb the energy of the beam. Thus the receivers must be in deserts or on very high mountains.
We thus arrive to the following comparison.

COMPARISON OF ORBITS

The three following almost circular orbits have been been compared.

A/ An heliosynchronous orbit"always entirely in the light of the Sun" at the altitude of 2000km with an inclination of 104°9 and a period of 127.2 minutes.

B/ An equatorial orbit at the altitude of 8 800km (period 5h10mn).

C/ A geosynchronous orbit (period 23h 56mn, altitude 35 800km) with an inclination of about 7°,

because of the luni-solar perturbations,and a small eccentricity in order to avoid, at least partially, the zone of space debris surrounding the geostationary orbit. (Space debris are of course dangerous for large structures).

The altitude 8800km of the orbit B is chosen because it is about halfway between the two radiation belts of the Earth at a minimum of radiation that is less that 10% of the two surrounding maximums that are respectively at the altitudes of 2800km and 14500km (see figure 4).

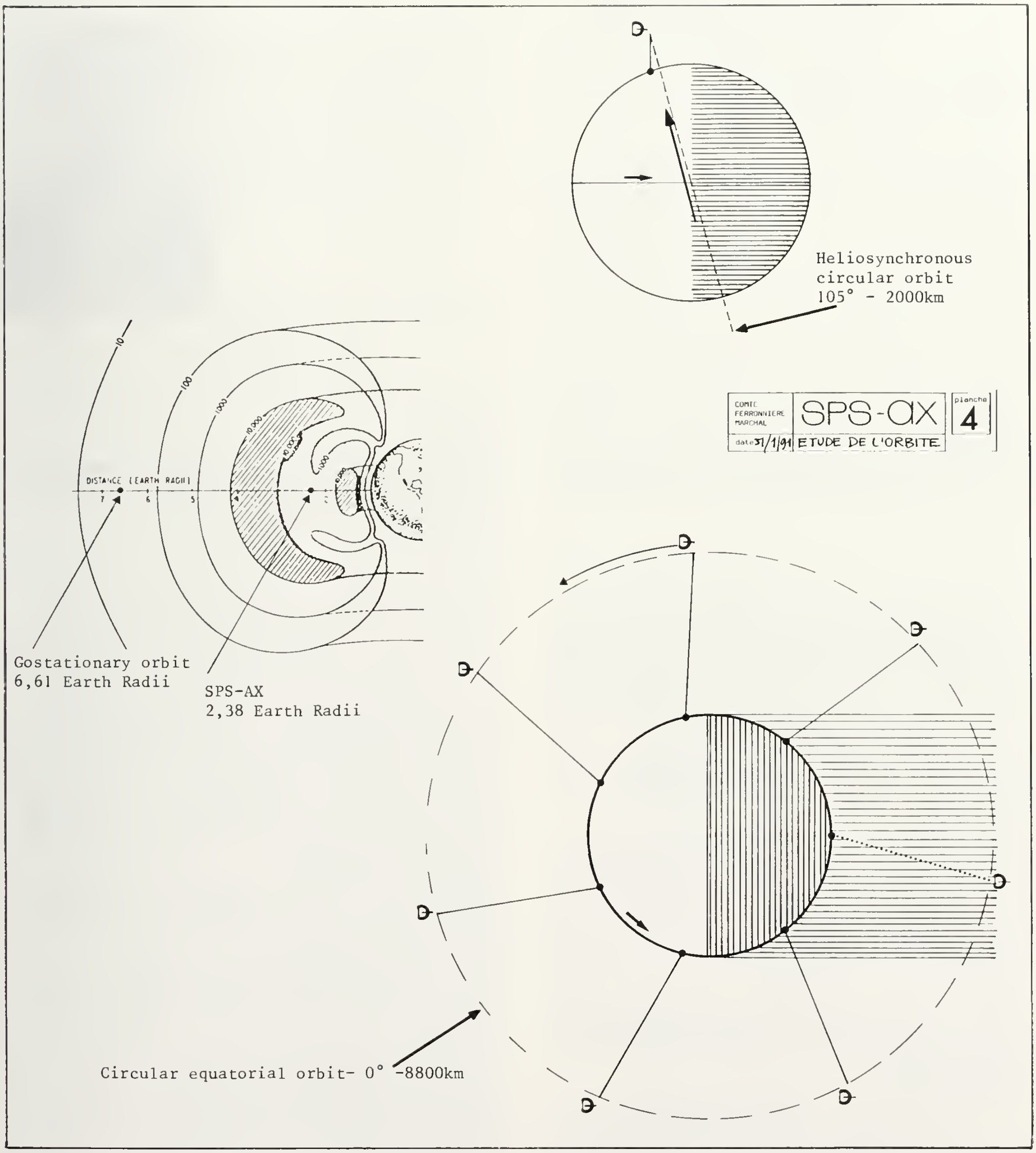
The difficulties of the Hipparcos satellite, on a wrong very eccentric orbit, have shown that it is possible to tolerate these radiation belts that Hipparcos crosses four times each day.

The general comparison leads to the following:

	ORBIT A	ORBIT B	ORBIT C
Altitude	2 000km	8 800km	35 800 km
Inclination	104°.9	0°	7°
Eccentricity	0	0	a few percents
Period	2h 7mn	5h 10mn	23h 56mn
Proportion of time in the light of the Sun (Earth shadow effects)	100%	90%	98.6%
Duration above 45° (zenithal passage above a receiving station)	8.6mn	1h 1mn (the synodic period is 6h35mn)	Indefinite if the satellite is at one of the four equilibrium longitudes *
Radiations	average	average	small
	can easily be beared		
Dangerous debris	rare	very rare	Numerous debris because of the proximity of the geostationary orbit
Miscellaneaous	Heliosynchronous orbit always entirely in the Sun light		Geosynchronous orbit near the geostationary orbit
Size of antennas:			
with microwaves ($\lambda \sim 12$cm)	metric size for experimental studies	500m to 1km	1 to 10km
with lasers ($\lambda \sim 9\mu m$)		10m to 20m	30m to 50m
Communications with the ground	irregular except for high latitude stations	regular (intertropical stations)	lasting if the longitudinal librations are small
DISCUSSION	A	B	C

A= convenient for an experimental study, but not for an industrial exploitation
B= almost equivalent to a continuous transmission if a crown of six or seven space stations faces the same number of ground stations (see figure 4).
C= The geosynchronous stations suffer from the large size of antennas.

* The four equilibrium longitudes of the geostationary orbit are the two longitudes of stable equilibrium 76° East (Sri Lanka) and 105° West (Mexico) and the two longitudes of unstable equilibrium 162° East (East of New Guinea) and 12° West (Sierra-Leone).
At the others longitudes the ordinary geostationary satellites are artificially stabilized, but this is difficult for large and brittle space stations that then, under the influence of the irregularities of the Earth potential,will have large longitudinal librational motions with generally a period of 2 to 3 years.



CONCLUSIONS

The first studies of large space power stations have been made with the utilisation of the geostationary orbit. However the perturbations and the large distance of this orbit lead to many difficulties,large antennas, many space debris, etc... Let us recall that space debris are very dangerous for large structures.

An equatorial circular orbit at an altitude of 8500 to 9000km, halfway between the two radiation belts seems much better and much more suitable especially if laser transmissions can be used,these laser transmissions that will be tested in the experimental study.

The drawbacks of this orbit and of laser beams: periodic transmission, absorption by clouds, are compensated by the use of a regular crown of six or seven space stations and by the same number of ground stations:

The transmission becomes almost continuous. The cloud absorption is avoided by ground stations in desertic areas or on the top of mountains that are particularly numerous between 25° North and 25° South even in the Pacific Ocean where we meet the high mountains of Java, Philippines,New Guinea and Hawaï.

For the experimental studies we don't need a mass production and it is preferable to test the laser transmissions on short distances. The heliosynchronous orbit "always entirely in the Sun" at 2000km altitude is then certainly the best orbit with a ground station at high latitude.

A6.3 Modeling of the development and infrastructure of solar electric power stations

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SUMMARY

The matematic models and computer's programs for total technical and economicresearch on Solar power stations have been developed.

RESUME

Des modèles mathématiques et des codes de calculs ont été développés pour la recherche technique et économique concernant les centrales électriques solaires.

The development of human activity in the area of adjacent and far-out space determines the interest for the creation of different-purpose orbital power complexes. Naturally enough that such power complexes are to be constructed on orbits which are most intensively exploited by different countries and which can, in this connection, serves as nodal orbits for the international colloboration.

Figure 1 demonstrates a variant of the energy complex, consisting of energy series meant for overlapping a wide class of problems, both immediate and long-term.

For system analysis and decision taking in developing the concept of energy series a job has been done for preparation of mathematical models and computer programs. A system of visual pictures-images is used, a successive change of which makes up a computer film. The succession of appearing visual images is subordinated to priorities of decision taking criteria.

The computer image provides dialog accompaniment of search studies and informs about a design variant of the infrastructure, both for energy series and for a space station at large, as well as co-ordinates the search strategy.

Each stage of space exploration is characteristic of its own level of power consumption. At present we see the ever-growing interest to power installations with the power over 100 kW. In this connection, more economic ways of power accumulation with respect to the means of delivery.

Schematic and arrangement solutions are under consideration for solar units with parabolocylindrical mirrors as the most compact when assembled. Solar power installations are made from similar element modules, that will enable, at the expense of unification of assembly technology, to form energy complexes with a wide range of powers in a short time and with minimum of expenses.

Base energy installations are most effective, each one being a complete unit of the corresponding energy series. The concepts of energy series are considered: hundreds and thousands kW.

Solar energy series are made up from the pairnumber, symmetrycally located as against the spacecraft independent energy modules, this providing the compensation of moments occured. The independent power module consists of three subsystems: a solar high-temperature heat source, jointed with a heat accumulator; a reset circuit for residual heat; a thermoelectric magnetic transformer operating in the Rankine closed cycle or in that of Brighton.

The development of a lay-out for the solar powermodule is illustrated on Fig.2. Roman figures stand for stages of deployment: I - the power installation arrangement out of 9 folded modules in transport position (cylindrical container); II - a folded power module in transport position; III - a folded power module in the pro cess of deployment; IV - a folded power module in operating position. Arab figures stand for the assemblies:

1 -a parabolocylindrical concentrator aligned mechanically with a radiator and consists of 10 panels of similar dimensions and structure.
2 - a preconcentrator combined with a radiation sensor and heat accumulator.
3 - a doubled non-moment unit of turbogenerators, consisting of two fully identic but oppositely located and synchronised thermoelectric magnetic transformers.
4 - a three-dimensional folded frame, pro viding necessary stiffnes of the module structure.
5 -local assemblies for opening and folding with elements of flexible transmission of the cooling agent from one panel of the radiator structure onto the other.
6 -the central assembly for opening and turning with necessary devices of flexible transmission of the cooling agent and energy to the customer.

Modular structures, as is known, allow to reduce the cost and operation, increasing the reliability of functioning as compared with similar by mission arrangements constructad by the principle of structural integrity.

The selection of design parameters of power modules for solar space electric power stations should be economically substantiated. This assumes that the constraints are to be observed for the cost of a product as well as the parameters of power modules must correspond to economically optimal values.

A procedure has been developed allowing to calculate optimal by cost parameters of the station's power modules (mass, electric power, surface area of the photocells and concentrators, safety characte-

ristics etc.). The procedure takes into account an uncertainty factor of the initial technical and economic information and serves as an instrument for correcting the sampling of design parameters for the station's power modules. In correspondence with calculations done by this procedure there has been found and quantitatively defined a tendency forincreasing the economically optimal power of energy module W^* with power growth of the solar space electric power station (Fig.3)

1 - a solar space electric power station based on turbogenerators;

2 - a solar space electric power station based on silicon photocells.

Further development of methods for economic estimation of powerfill solar space electric stations assumed a wide use of the instrument for imitating modelling and theory of economic risk.

To solve the accompanying problems in forming the energy series we analyze methods for improving the processes of solar, nuclear and combined power facilities. Optimization studies go in a specially prepared intellectual computer medium. The intellectual computer medium is an object-oriented information environment for purpose improvement of energy-forming structures of power installations and solar power installations based on the experiense gained during the design-search studies. The search goes by a scenario, which is a record of programs and a list of computer images, determining the priority of their engagement into the optimization process for solving the chosen global problem. To create a participation effect there are also engaged computer sceneries, determining a structure of the problem as a sequence of action areas of energy means of a spacecraft (Fig.4). Till altitude H1 (reference orbit) the area of reusable aerospace vehicles, the operation of which on cargo delivery is regulated by the number of launches and modules per firing, as well as by the orbital inclination of a carrier. Fufther grading of areas is defined proceeding from variants of engagement of engine-power means. A variant is foreseen when the power plant-and the unit of electric rocket engines of an inter orbital spacecraft is fired from a transfer orbit H3, to which it is put by means of the in terorbital transport vehicle. The interorbital transport servicing vehicle with engines of short duration (liquidpropellant rocket engine, solid-propellant rocket engine, nuclear rocket engine) provide: delivery of the interorbital spacecraft on radiation-save orbits; delivery of transport units to altitudes with lower level of gravity; quick redeployment of satellite modules beyond radiation belts. It is visually observed how the interorbital spacecraft performs a transfer between orbit H3 and operating orbit H2 and how the condition is controlled the total mass of cargo, delivered to altitude H2 and of propulsive mass necessary for the interorbital spacecraft, should not exceed the lifting power of a transportation spacecraft. Area HX is separated, as it assigns the altitude of a return orbit. Area HX - H1 defines self-return of the vehicle into a reference orbit at the expense of aerodynamic braking. In accordance with a location of the vehicle in visually observed areas there goes a criterion control over space situations and a necessary correction of characteristics of the space systems. The optimization process develops by the principle of a computer film, the replacable stills (computer windows, Fig.4) defining the order of decision taking counting for global aims of optimization. Power plants and solar power plants are under study in their different schematic and arrangement implementation for various space programs, in conjunction to different means of delivery.

An appropriate spacecraft is sampled with optimal relative mass of the useful cargo $\gamma_{к}$ with respect to real time of transport operations-τ, real thrust-P and thrust specific impulse-$P_{уд}$ of engines and to real characteristics of power means. The attention is concentrated only on that space versions, which are in the domain of real criterion indices.

The structure on Fig.4 helps to analyze a wide range of variants and, in particular, obtain optimal parameters to form the infrastructure of energy series of solar space electric stations. Studies have been made of many variants for delivery problems using the interorbital transport vehicles (based on chemical engines, solar installation with a turbogenerator, combined solar-nuclear system, nuclear rocket engine) for cargoes in the direct and back flights into a geostationary orbit at flights' inclination orbits 47, 68 etc. In particular, for 10 flights the interorbital transport vehicle is able to deliver cargo into a geostationary orbit, thus making it possible to arrange a space power complex with 8000 kW at specific mass of the electric power plant over 15 kg/kW. This complex, for instance, can provide SHF energy transmission or by means of a laser beam to space, airborne or ground objects.

LEGENDS OF THE FIGURES

Fig.1. A variant of the power complex consisting gradually growing in number energy series.

Fig.2. A lay-out of the solar energy module.

Fig.3. Economically optimal powers of energy modules (W^*) for solar space electric power stations.

Fig.4. Computer representation of action zones of the spacecrafts when forming space energy complexes.

1-information window for final characteristics;
2-window of a design analysis for the interorbital transport vechicle variants;
3-window of a design analysis for stages;
4-window of a variant for the power plant;
5-window of a variant for the propulsion system;
6-window of variants for carriers
ZNH-0 expendable rocket carriers
ZNH-1 reusable transport aerospace vehicles
7-window of a design image for the interorbital transport vehicle variant;
8-KL-window of variant succession: 1,2-electric rocket engines, 3-solid-propellant rocket engines, 4-liquid-propellant rocket engines, 5-nuclear rocket engines;
9-window of control;
10-window, image of a redeployment stage;
11-windows, comments;
12-succession of computer windows, decision taking;
13-plane of equatorial orbit;
14-UKP- freight traffic of the interorbital transport vehicle with electric rocket engine to τ^+ and back τ^- ;
15-zone boundary for intensive radiation;
16-ZNH-number of launches of rocket carriers and transport aerospace vehicles;
17-UKO-freight traffic of auxilliary stages to τ^+ and back τ^- ;
18-shadow boundary, inclination, space station - duration of shadow sections;
19-TM- object capture time in the corridor of altitudes (Δ h);
ZNM- number of the power plant ignitions;
20- τ_c - aerodynamic braking time during

the return of an object from an operating orbit to a reference orbit;

21-m^0 - launching mass of units docked in the operating orbit;

22-H1- reference orbit;

23-HX- operating orbit;

24-H3- transfer orbit;

25-H2- working orbit;

26-next operations of the far space exploration with respect to the base power complex formed in orbit H2.

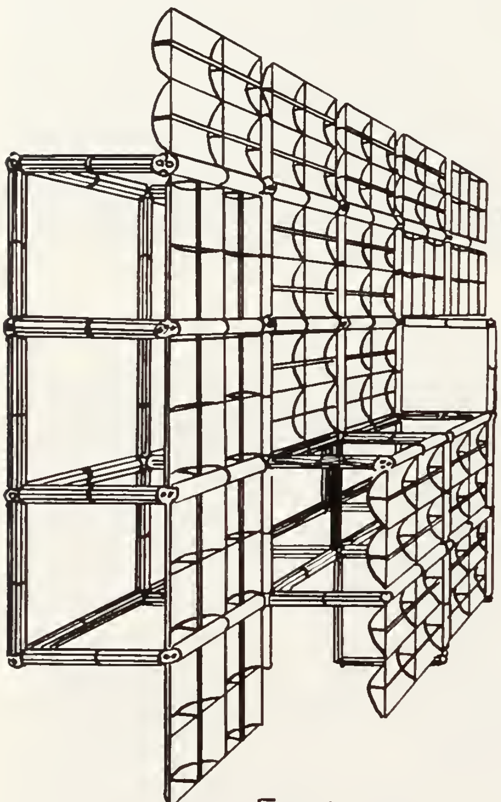

Fig.1

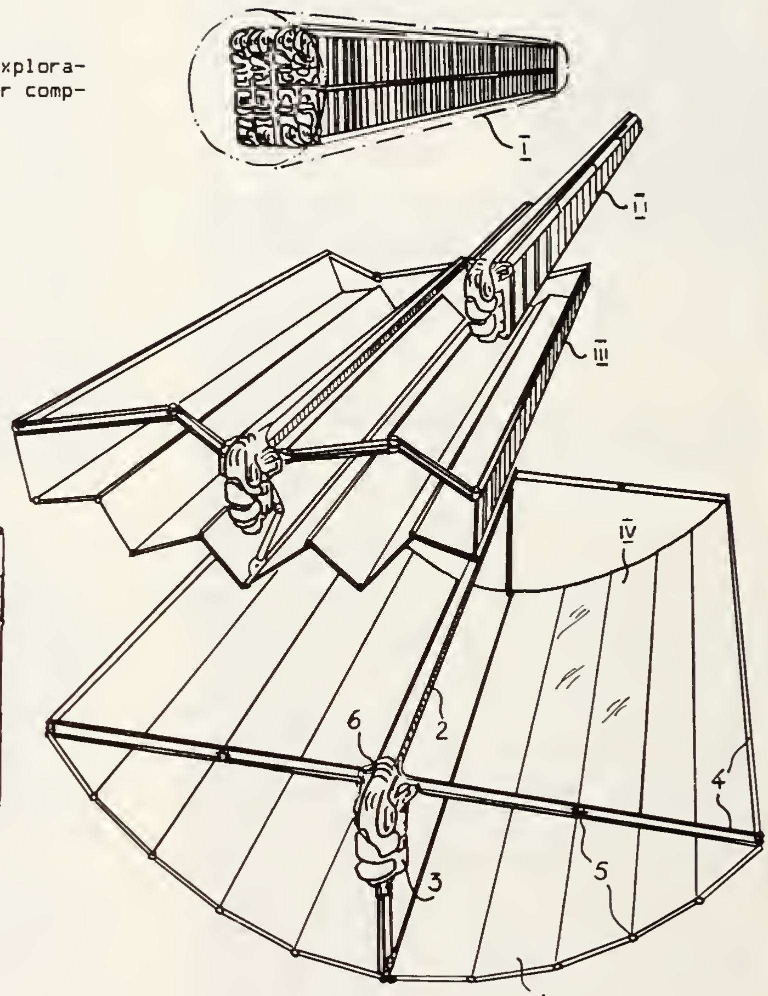

Fig.2

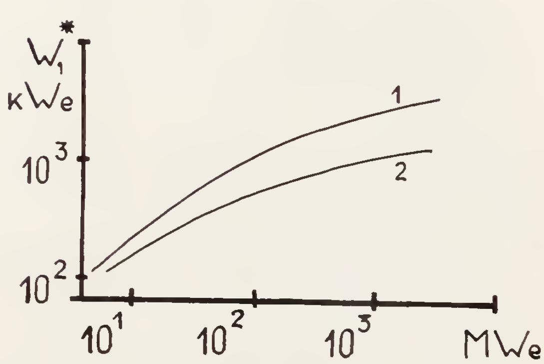

Fig.3

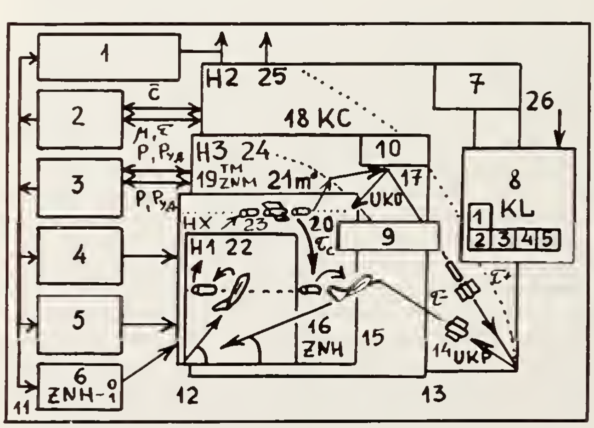

Fig.4

SPS 91

A6.4 The complexation method of energy generation and angular motion control systems for space solar energy station concept

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ABSTRACT

Analitical technique applied for solving optimizational problems at structural parametric synthesis of main space solar energy station subsystems is discussed. The characteristic of the program modeling complex software allowing to investigate the interaction of positioning and angular motion control system, solar batteries and active phased array at functioning is presented.

RESUME

Cette communication présente une technique analytique d'optimisation des principaux sous-systèmes des centrales solaires spatiales SPS. On présente l'outil de modélisation permettant d'étudier le système de positionnement d'une centrale solaire orbitale tant en ce qui concerne les panneaux solaires qu'en ce qui concerne l'antenne d'émission constituée de réseaux phasés.

INTRODUCTION

The modern estimations of creation and use expediency of space solar energy stations (SSES) with the energy transmission purpose to the Earth as VHF emission, based mainly on analysis results and structural and parametric synthesis of its certain subsystems: solar batteries (SB), VHF emission generator, and active phased array (APA) [1-3]. Herewith the SSES efficiency estimation had been carried out, as a rule, ignoring the features of their joint functioning, environmental influence as well as energetical and dynamical interaction with other subsystems, and first of all with the positioning and angular motion control system (PAMCS) of the SSES constructional units. Such an approach to the grade determination is justified when considering the SSES with the conventional planar SB, output characteristics whereof are not critical to the accuracy of the boards orientation towards the Sun. At the same time as an alternative variance considered there are SB with sun radiation concentrators (SRC). The later in some cases allow to reduce the cost and raise up durability of SSES, however there is a need of substantionally higher accuracy of their orientation to the Sun. The necessity of loss reduction (such as energy, information in the link systems, ecological etc.) when transmitting VHF emission also requires an increase of APA aiming to receivers. However as SSES makes a multiplelinks object with constructional units of limited stiffness then a maintenance of a high accuracy orientation of one of the units (e.g. APA) makes the solution of the same problem for others (e.g. SB with SRC) more complicated. The indicated circumstances underline the demand of the systems complexation based upon the solution of energetic and dynamic compatibility problem of PAMCS and other constructional units of SSES (APA, SB etc.)

1. PROBLEM FORMULATION

In making SSES image characterised by main subsystems parameters vector $\mathbf{a}_i \subset \{\mathbf{a}_i\}$, the basic demand is to provide the required energy supply level $\mathbf{P}^a_\tau \geqslant [\mathbf{P}^a_\tau]$, determined by average annual useful power $\mathbf{P}^a_\tau$ during the active functioning time interval τ ($\tau=\overline{1,N}$ years). Solving this problem in optimizational statement it is necessary to use indexes of SSES functioning economic effectivness. As one of the indexes a profit C can be used, that is computed as summary income difference from selling energy C^Σ_b to consumers during a given period of time τ and expenditures C^Σ_l of SSES life-cycle:

$$C = C^\Sigma_b(\mathbf{P}^a_\tau, c^b_m, \mathbf{a}_i) - C^\Sigma_l(\mathbf{P}^a_\tau, c^l_m, \mathbf{a}_i).$$

Here the following notations are used: c^b_m - a predicted average energy cost level; c^l_m - a predicted average cost of unsupplied ecologycal losses, additional technical measures to avoid them, and besides fines compensating negative effects of SSES developing and functioning.

Let's discuss life-cycle specific cost indexes expenditures c^c_i for k SSES main subsystems. Taking into account expenditures due to ecological and other losses, and also the expenditure for their prevention and compensation with specific cost indexes c^l_j a complex economic quality index can be presented as:

$$\mathbf{F}(\mathbf{a}_i) = \sum_{i=1}^{k} c^c_i \mathbf{P}^g_\tau(\mathbf{a}_i) + \sum_{j=1}^{l} c^l_j \mathbf{P}^l_\tau(\mathbf{a}_i) \quad ,$$

where $P^g_\tau, P^l_\tau (P^l_\tau \leqslant P^l_\tau)$ - are the meaning of SSES output power and microwave power level emission, that can be result in nega-

tive functional effects. As the specific cost indexes during some finite SSES life-cycle intervals are the limited values $C_i^c \leqslant [C_i^c]$; $C_j^l \leqslant [C_j^l]$, the SSES structural parametric synthesis problem in optimizational statement can be formulated as mathematic programming task:

$$\begin{cases} \min\limits_{a_i} F(a_i) = \min\limits_{a_i}\left[\sum\limits_{i=1}^{k} c_i^c P_\tau^g(a_i) + \sum\limits_{j=1}^{l} c_j^l P_\tau^l(a_i)\right] \\ P_\tau^a(a_i) \geqslant [P_\tau^a]; \quad a_i \subset \{a_i\}, \end{cases} \quad (1)$$

The main idea of the proposed complexation method is the development of a set of interconnected mathematical models describing the processes of SB,APA and PAMCS joint functioning (structural flux diagram of this processes is given in Fig.1) and solving SSES image formation task according to the (1) statement using classical methods of object function extremum search.

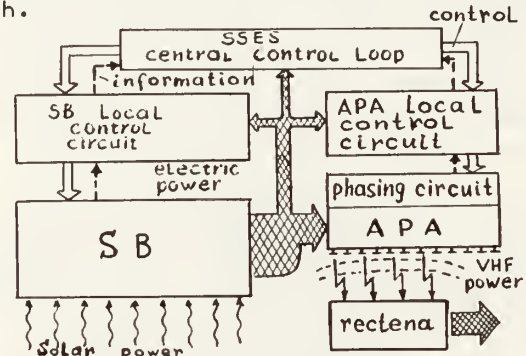

Fig.1 SSES structural flux diagram

2. PROGRAM MODELING COMPLEX CHARACTERISTIC

The bases of program modeling complex is mathematic models of energetic processes in SB of planar and concentrating types, model of generating and emission of microwave power, finite dimensional mathematic model of SSES controlled angular dinamics,and besides the aggregate of guidance algorithms in SSES angular motion and relative movement of construction components (SB,APA). Realization of suggested method with the use of program modeling complex is achived by means of introduction the aggregate of investigated interaction processes models.

2.1. Energetic model of solar batteries functioning

Mathematic model of SB functioning describes the processes of solar emission concentration to the solar cells (SC) surface, transformation of it into electric power,heat removal, SRC and SC characteristic degradation under the influance of highenergy charged particles of Earth radiational belts and solar cosmic beams, and besides collecting current by SB commutation elements.

Photometric method is developed for SRC modeling, based on tracking beam dirrect passage in multimirror system and modeling the luminance distribution of emmission reflected from the surface elements of mirrors. Linear and angular disalignments of mirrors,orientation errors of SRC to the Sun, statistical irregularities of reflecting surfaces, luminance distribution along the Sun disc, and also indicatrix of emission diffusion by mirror reflecting surface are taken into account in the computational algorithm.

The main idea of this method is following.Over of SRC entrance aperture (Fig.2) a primary coordinate grid 1 is formed,that is perpendicular in direction to the Sun.

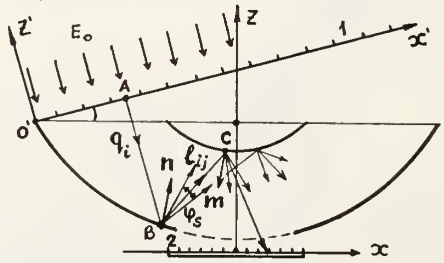

Fig.2 Geometrical model of beams passage

From the middle of every i -th coordinate grid cell is q_i beam is emitted, that is parallel in direction to the Sun. After that the coordinates of beam point intersection with the surface of primary mirror and angular coordinates of normal n direction to this surface taking into account its irregularities that are modelled by the universal generator of random numbers having normal distribution law are determined. Then the direction of beam q_i mirror reflection (beam m_i) is computed and in the vicinity of this direction a "fan" of beams l_{ij} is emitted into the region limited by the solar disk angular dimensions and diffusion indicatrix.Luminance emission in the direction l_{ij} is computed according to the formula

$$B(\varphi_B) = \frac{\rho_\varphi \, E_0 \, \chi_\Sigma \, k_s}{\pi \quad \varphi_s^2 (1+ d_s)} \left(1+d_s\sqrt{1 - \varphi_B / \varphi_s}\,\right),$$

where: E_0 - Solar's constant; ρ_φ - is the emission reflection coefficient in the direction of φ_B , determined by the diffusion indicatrix; φ_s - is the angular solar disk parameter; χ_Σ - is Heavyside's function characterising the fulfilment of a set of conditions when the solar disk is visible from considered point B ; k_s= 1.255 and d_s= 1.564 are the approximation coefficients. After that a further tracking of every beam passage up to its intrsection with SC surface,in this case the beam luminance are multiplied through reflection coefficients that are the angle incidence emission functions. Having determined the beam point intersection coordinates with the SC surface, cell indeces of its coordinate grid are found. In this case the illuminance of this cell increases in proportion to the luminance of beam that reached it. As a result of tracking all the beam emitted by SRC primary coordinate grid , the illuminance distribution of the whole SC and solar emission concentration average coefficient k_c are estimated.

On computing Cassegranian's system using this method, the analytical dependence of k_o on SRC disorientation angle υ_s

was obtained

$$k_o = k_p (r_1^2 - r_2^2)\ [\ \exp\ (-\ a_\nu^2\ \upsilon_s^2 / W_\nu^2\ )]/r_2^2,$$

where: k_p - is the interception emission coefficient at $\upsilon_s = 0$; r_1 and r_2 - are the radii of primary and secondary SRC mirrors; a_ν and W_ν - are approximation coefficients.

A relative energy pick off coefficient for a couple of planar (ν= p) and concentrative SB (ν= c) is computed in accordance to equation

$$K_E^\nu = \frac{1}{2}\left(\sum_{i=1}^{2} E_i^\nu \ /\ E_0^\nu \right) / T_{st}\ ,$$

where: $E_i^\nu = \sum_{m=1}^{p} E_{im}^\nu$; $E_{im}^\nu = E_0 \int_0^{T_{st}} K_d^\nu K_c^\nu dt$ -

is averaged energy pick off at the specific time interval $[0, T_{st}]$ for planar and concentrative SB taking into account the errors of their orientation to the Sun;

$$K_c^p = \cos\left(\alpha_{im}^\Sigma (t) \right);$$

$$K_c^c = \exp\left[-\ \alpha_{im}^\Sigma (t) / (a\ W^2) \right] dt;$$

$$K_d^\nu = K_o^\nu\ (\ 1 - \Delta_\nu \tau)\ ,\ \nu = \{p, c\}\ -$$

are the time degradation coefficients of SB specific energetic characteristic mentioned above; Δ_ν - is the degradation parameter per year; τ- is time parameter (in years of SSES active functioning); a , W - are constants characterising concentrative SC optical properties;

$$\alpha_{im}^\Sigma(t) = \alpha_{im}(t) + \Delta\gamma(t)$$

is the SC deviation summary angle from the direction to the Sun; α_{im} - is the SC deviation angle caused by SB elastic deformation; E_0^ν - are the maximum amounts of instant energy pick off ($\alpha_{im}^\Sigma(t) = 0$) from one SB cell.

The influence of increased illuminance and temperature at the process of generation, diffusion, recombination and tunnelling of charge carrier in the structure of heteroface SC is taking into account solar emission transformation model. The affect of cosmic radiation at SC characteristics is modelled by degradation coefficients, life-time and speed of minority carrier surface recombination as a function of proton equivalent flux density F_{ek} with 20 MeV energy.

The analysis of SRC construtïon screen affect allowed to get the following flux dependence F_{ek} on the SC thickness of screen coat δ, on primary and secondary mirrors radii r_1 and r_2 on the SSES orbit time functioning τ

$$F_{ek} = \tau\ \exp[a_{p1}(1 - a_{p2} \ln\delta)\ ](1 - a_{p3} r_2\ /\ r_1)$$

where: a_{pi} - the approximation coefficients.

Analytical model of radiative and conductive heatremoval from concentrating type SC with SRC is got at the basis calculus of variations method using a new criteria of heat simularity, which for ring emitting rib has the following form:

$$B_T = Q_T\ (\ r_e\ /\ r_o) / (\ \lambda \delta\ T_a),$$

$$T_a = \sqrt[4]{Q_T\ /\ (\ \varepsilon_\Sigma\ \sigma_B\ \pi\ (\ r_e^2 - r_o^2))}\ ,$$

where: Q_T - is the heat flux led to the basis of the rib; δ , λ - is the rib thickness and heatconductivity correspondingly; ε_Σ - is the total emission capability of front and back rib surface; r_e ,r_o - are the radii of basis and face rib surface; σ_B -is the Stephan-Boltsman's constant.

As a result a rather simple dependence is derived for temperature distribution along the emitting rib surface

$$T_r = T_a \left\{ 1 + B_T^{\alpha_{TO}} \left[\alpha_{T1} \sum_{i=1}^{4} \left[(-1)^n (\chi_i - f_T)(1 - \bar{\mu}\ )/n \right] \right] \right\},$$

where: $\chi_2, \chi_4 = 1; \chi_3 = 0;\ \mu = r/r_o;\ \mu_e = r_e/r_o;$ $f_T = (\mu_e - 2)\exp(1 - \mu)\ _{T2};\ \bar{\mu} = (\mu_e - \mu)/(\mu_e - 1);$ α_{TO}, α_{T1} -are approximation coefficients.

2.2. Microwave power generation and transmission model

Coordinate projection methods of rectenna's receiving elements on the cross-sectional beam plane was applied for modelling the distribution of microwave emission intensity at the surface of rectenna taking into account guidance errors of APA directional diagram. Besides Gauss's beam density distribution in beam section was discussed (Fig.3)

$$q_r = q_o\ \exp(\ -\ 2\ r^2 /\ r_e^2\ )\ .$$

where: r-is a radius vector of a point in the cross-sectional beam plane; q_o - is the intensity value on the axis of the beam; r_e - is a normalizing beam radius, which is determined by difractional divergence of emission θ_d and by the directional diagram width θ_a

$$r_e = L\ (\ \theta_a + \chi_f\ \lambda\ /\ D_a\ )$$

where: L- is the distance from APA to rectenna; λ - is the length of emission wave; D_a - is the diameter of APA aperture ; χ_f - is the coefficient characterizing wave front imperfection.

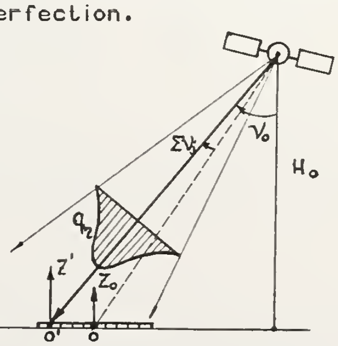

Fig.3 Emission distribution at cross-sectional beam plane

Emission intensity $q_i(x,y)$ at i-th rectenna's elements is determined by coordinates of its projection x_i ,y_i on the cross-sectional beam plane

$$q_i(x,y) = q_r\ \cos\ (\ \nu_o + \sum_{j=1}^{k} \nu_j\ )\ ,$$

where: ν_o - is the angle of emission incidence at perfect APA orientation to rectenna with non-zero geografic latitude of arrangement; ν - are the pointing errors of APA directional diagram due to the orientation errors of APA- based coordinate system, phasing errors and errors due to the SSES's orbit statement east-west drift and inclination.

Calculation of average power P_a generated by rectenna during equal to time constant T_{st} of APA angular motionis made by the integration of partial power of rectenna elements taking into account their commutation circuit at the moments of real emission reception

$$P_a = \frac{\eta_o \eta_t}{T_{st}} \int_o^{T_{st}} \chi_\gamma \sum_{i=o}^{n} q_i(x,y)\, d\tau ,$$

where: η_o - is the coefficient of emission attenuation by environment; η - transformation efficiency of microwave emission into the electric power; n - a number of elements in rectenna; χ_γ - is the Heavyside's function the value of which is determined by the emission mode.

2.3. Station dynamic and angular motion control model

A separate SSES energy-emitting module as a mechanical system is represented as a carrier absolutily rigid body and N elastically deformed elements (EDE) that suit the system of the least stiff construction components (SB and APA). Coordinate system O_{xyz} is connected with carrier body (Fig.4) and its motion is determined by the speed vector V_0 of linear motion pole O and by the angle speed ω vector of rotation relative to some inertial frame $O_{\chi\eta\zeta}$

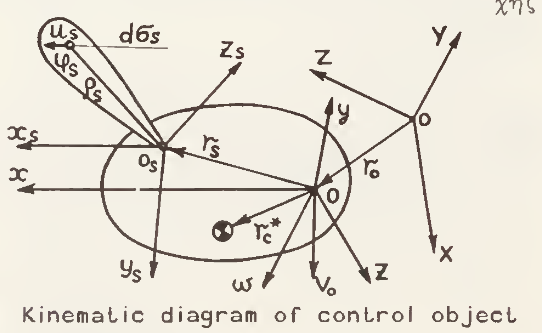

Fig.4 Kinematic diagram of control object

Let's consider SSES coordinate system O_{xyz} the following three dimensional bases: Φ_0-for carrier body; Φ_k- for k -th EDE, that are in the original form (without any deformation). Elementary particles of EDE with original volumes $d\sigma_k \subset \Phi_k$ and masses dm_k ($k = \overline{1,N}$) are represented as material points with radii-vectors (ρ). In this case according to Lurie's method , the EDE point elastic displacement vector u can be represented as:

$$u(\rho) = \sum_{s=1}^{n} q_s \Lambda_s(\rho) + \frac{1}{2} \sum_{s=1}^{n_o} \sum_{\nu=1}^{n_o} q_s q_\nu \Lambda_{s\nu}(\rho) + \ldots, \quad (2)$$

where: $\Lambda_s(\cdot)$, $\Lambda_\nu(\cdot)$, $s,\nu = \overline{1,n}$ - is some system of vector-functions ,determined on $\Phi = \sum_{k=0}^{N} \Phi_k$,and n_o-is the summary parameters number q_s.

Flexible station dynamic is described by Euler-Lagrange's equations in accordance to [7]

$$\Im_0 \dot{\omega} + \rho_q \times \overset{*}{V}_0 + \sum_{s=1}^{n_o} \ddot{q}_s a_s = p^\omega(M^o, \omega, V_o, q_s, \dot{q}_s);$$

$$m_0 \overset{*}{V}_0 + \dot{\omega} \times \rho_q + \sum_{s=1}^{n_o} q_s b_s = p^v(R^o, \omega, V_o, q_s, \dot{q}_s); \quad (3)$$

$$\sum_{\nu=1}^{n_o} A_{s\nu} \ddot{q}_\nu + (b_s + \Delta b_s)\overset{*}{V}_o + (a_s + \Delta a_s)\dot{\omega}_o =$$
$$= p_s^q(Q_s^o, \omega, V, q_\nu, q_\nu, \nu = \overline{1,n_o}), \quad s = \overline{1,n_o}.$$

Here: $(*)$-is a local derivative in time;

$$\rho_q = m_0 \rho_0 + \sum_{s=1}^{n_o} q_s b_s; \quad \Im_0 = \Im^o + \Delta\Im_q = \Im^o + 2\sum_{s=1}^{n_o} q_s \mathbb{A}_s;$$

m_0-is summing mass SSES; ρ_0-is mass center radius-vector of SSES, solidified in the original state (SOS); $\Im^o$ - SOS station inertia tensor;

$$\Delta b_s = \sum_{\nu=1}^{n_o} q_\nu \beta_{s\nu}; \qquad \Delta a_s = \sum_{\nu=1}^{n_o} \dot{q}_\nu \alpha_{s\nu};$$

$$p^\omega(\cdot) = M^o - \sum_{s=1}^{n_o} \dot{q}_s \left[2\mathbb{A}_s \omega + \omega \times a_s - \mu_s' \right] -$$
$$- \sum_{s=1}^{n_o} q_s \left[\omega \times \mathbb{A}_s \omega + b_s \times (\omega \times V_o) - \mu_s \right];$$

$$p^v(\cdot) = R^o - \sum_{s=1}^{n_o} \dot{q}_s \left[2\omega \times b_s - u_s' \right] -$$
$$- \sum_{s=1}^{n_o} \dot{q}_s \left[\omega \times (\omega \times b_s) - u_s \right];$$

$$p_s^q(\cdot) = Q_s^o - \sum_{s=1}^{n_o} \dot{q}_s \left[(b_{s\nu} - r'_{s\nu})\dot{q}_\nu + \right.$$
$$\left. + (c_{s\nu} - r_{s\nu}) q_\nu \right] - (b_s + \Delta b_s)(\omega \times V_o) +$$
$$+ \omega \left[(\mathbb{A}_s + \sum_{\nu=1}^{n_o} q_\nu \mathbb{B}_{s\nu}) \omega \right] + 2\omega \sum_{\nu=1}^{n_o} \Gamma_{s\nu} \dot{q}_\nu;$$

where: $M^o = \int_\varphi \rho \times F^o d\sigma$; $\quad R^o = \int_\varphi F^o d\sigma$;

$$Q_s^o = \int_\varphi F^o \Lambda_s d\sigma; \quad F^o(\rho), \ \forall \rho \in \Phi$$

are volume surface linear-distributed and/or concentrated forces acting upon the SOS station according to a given design-arrangement scheme.

$$\mu_s = \int_\varphi (\rho \times f_s + \Lambda_s \times F^o) d\sigma; \ \mu_s' = \int_\varphi \rho \times f_s' d\sigma; \ u_s = \int f_s d\sigma;$$

$$u_s = \int_\varphi f_s' d\sigma; \ r_{s\nu} = \int_\varphi (f_\nu \Lambda_s + F^o \Lambda_{s\nu}) d\sigma;$$

$$a_s = \int \rho \times \Lambda_s \ldots; \ \alpha_{s\nu} = \int (\Lambda_s \times \Lambda_\nu + \rho \times \Lambda_{s\nu}) \ldots; \ b_s = \int \Lambda_s \ldots;$$

$$b_{s\nu} = \int \Lambda_{s\nu} \ldots; \ A_{s\nu} = \int \Lambda_s \Lambda_\nu \ldots; \ \Gamma_{s\nu} = \int \Lambda_s \times \Lambda_\nu \ldots;$$

$$\mathbb{A}_s = \int [(\rho \ \Lambda_s)\mathbb{E}_3 - \tfrac{1}{2}(\rho \Lambda_s^T + \Lambda_s \rho^T)] \ldots;$$

$$\mathbb{B}_{s\nu} = \int [(\Lambda_s \Lambda_\varphi)\mathbb{E}_3 - \tfrac{1}{2}(\Lambda_s \Lambda_\nu^T + \Lambda_\nu \Lambda_s^T) + (\rho \ \Lambda_{s\nu}^T)\mathbb{E}_3 -$$
$$- \tfrac{1}{2}(\rho \Lambda_{s\nu}^T + \Lambda_{s\nu} \rho^T)] \ldots; \ r'_{s\nu} = \int f_s' \Lambda_\nu d\sigma.$$

Here: $c_{s\nu}$ and $b_{s\nu}$ are quasielastic and dissipative coefficient; f_s, f_s', $s = \overline{1,n_s}$ - is coordinate and rate correction

in the model of force action $\mathbf{F}$ on the object construction:

$$\mathbf{F} = \mathbf{F}^o + \sum_{s=1}^{n_o} (\mathbf{f}_s q_s + \mathbf{f}'_s q_s).$$

Adding kinematic relationships into the system (3) excluding orbital linear movement dynamics from consideration, aligning the coordinate basis pole $\mathbf{O}$ with mechanical system mass center ($\rho_o = 0$),and also choosing the vector-function system $\mathbf{\Lambda}_s$ corresponding to $[A_{s\nu}] = \mathbb{E}_{n_o}$, let's present the system equation (3) solution relative to the highest derivatives in the form:

$$\begin{cases} \dot{\varphi} = \Phi(\varphi)\omega; \ \dot{\omega} = \mathbf{U}_r(\omega) + \mathbf{U} + \mathbf{U}_v \ ; \\ \ddot{\mathbf{q}} + \mathbb{D}(\vartheta)\dot{\mathbf{q}} + \mathfrak{R}(\vartheta)\mathbf{q} = \mathbf{V}(\vartheta) + \mathbf{W}(\dot{\omega}) + \mathbf{g}, \end{cases}$$

where:

$$\Phi(\varphi) = \begin{bmatrix} \dfrac{\cos\varphi_k}{\cos\varphi_j} & -\xi\dfrac{\sin\varphi_k}{\cos\varphi_j} & 0 \\ \xi\sin\varphi_k & \cos\varphi_k & 0 \\ -\xi\operatorname{tg}\varphi_k\cos\varphi_j & \sin\varphi_k\operatorname{tg}\varphi_j & 1 \end{bmatrix};$$

$$\xi = \begin{cases} 1, \text{ at } ijk = 123 \vee 231 \vee 312; \\ -1, \text{ at } ijk = 132 \vee 213 \vee 321. \end{cases}$$

$$i,j,k = \overline{1,3};\ i \neq j \neq k;$$

$$\varphi_{<3>} = \{\varphi_i, \varphi_j, \varphi_k\}^T, \ \omega_{<3>} = \{\omega_i, \omega_j, \omega_k\}^T -$$

are the angles vector and angular motion projections vector in $\mathbf{O}_{xyz}$ base; $\mathbf{U}$-control action vector; $\mathbf{U}_v = \mathbf{U}_q(\mathbf{q}) + \mathbf{U}_B$ - disturbance acceleration vector due to dynamics of EDE and other types of inner and outer disturbances $\mathbf{q}_{<K>} = \mathrm{col}(\mathbf{q}_s,\ s = 1,N)$

$$\mathbf{V}_{<K>}(\vartheta) = \mathrm{col}(\mathbf{V}_s(\vartheta)); \ \mathbf{W}_{<K>}(\dot{\omega}) = \mathrm{col}(\mathbf{W}_s(\dot{\omega}));$$

$$\mathbf{g}_{<K>} = \mathrm{col}(\mathbf{g}_s); \quad \mathbb{D}_{[K,K]} = \mathrm{diag}\{\mathbb{D}_s, \};$$

$$\mathfrak{R}_{[K,K]} = \mathrm{diag}\{\mathfrak{R}_s\}; \quad s = \overline{1,N} \quad K = \sum_{s=1}^{N} n_s.$$

The desired dynamics of SSES body with actuators of APA and SB (which orientation to satisfy the most stress requiments) attached to it will be determined by based trajectory found at a number of differential equation system solution in the form:

$$\dot{\varphi}_o = \Phi(\varphi_o)\omega_o; \quad \dot{\omega}_o = \mathbf{U}_g(\omega_o) + \mathbf{U}_o,$$

where: $\varphi_{o<3>}, \omega_{o<3>}$ - are angle and angular rate vectors on the based trajectory; $\mathbf{U}_g(\omega_o) = -\mathcal{J}^{-1}(\omega_o \times \mathcal{J}\omega_o)$, $\mathbf{U}_o$- are vectors of body acceleration due to gyroscopic links, and controlling acceleration, that is formed by SSES actuators and performed the undisturbed based motion in the "solid" state.

Quasisolidification condition [8] will be put down in the form

$$\|\mathbf{U} - \mathbf{U}_o + \mathbf{U}_g(\omega) - \mathbf{U}_g(\omega_o) + \mathbf{U}_q(\ddot{\mathbf{q}}) + \mathbf{U}_B\| \leqslant \varepsilon^*$$

where ε^* -is the parameter characterizing the rate of simularity of the object real dynamic to assigned based motion.According to invariant synthesis theory the central control $\mathbf{U}$ may be divided into the based $\mathbf{U}_o$ and "synthesising" $\Delta\mathbf{U} = \Delta\mathbf{U}(\varphi,\omega,\mathbf{q},\dot{\mathbf{q}},\mathbf{U},\vartheta,\mathbf{U},\mathbf{g}^o)$ components.

To decrease disturbance level due to EDE dynamic it is proposed to supply the transition of flexible system into the stationar state corresponding of active loading applying to object a profilled control and using the local tools for oscillator active damping [8]:

$$\ddot{\mathbf{q}}_s = 0; \ \dot{\mathbf{q}}_s = 0;$$

$$\mathbf{q}_s = \mathfrak{R}_s^{-1}[\mathbf{V}_s(\vartheta) + \mathbf{W}_s(\dot{\omega}) + \mathbf{g}_s] \quad s = \overline{1,n}.$$

At ideal conditions $\mathbf{U}_q(\ddot{\mathbf{q}}_s, s = \overline{1,n}) \equiv 0$.

"Sythesising" component $\Delta\mathbf{U}$ can be formed using information $\mathbf{Y}_{\dot{\omega}}$ about an object body angular acceleration.

$$\Delta\mathbf{U} = -\mathbf{Y}_{\dot{\omega}} + \mathbf{U}_g + \mathbf{U}(\omega_o).$$

Here $\mathbf{U}$ - is the instant value of central control."Sythesising" component $\Delta\mathbf{U}$ in accordance to Petrov's two channels control principle is formed as $\Delta\mathbf{U} = \Delta\mathbf{U}_f + \Delta\mathbf{U}_p$, where $\Delta\mathbf{U}_f$, $\Delta\mathbf{U}_p$- are components that are formed by primary (disturbance compensating) and fine (disalignment compensating) control loops.

As an example of fine control loop it is proposed to use optimized on quadratic criteria position and rate control

$$\Delta\mathbf{U}_f = \mathbb{K}_1\Delta\varphi + \mathbb{K}_2\Delta\dot{\varphi},$$

where

$$\Delta\varphi = \varphi - \varphi \ ;$$

$$\Delta\dot{\varphi} = \dot{\varphi} - \dot{\varphi}_o = \Phi(\varphi)(\omega) - \Phi(\varphi_o)\omega_o;$$

$$\mathbb{K}_1 = \mathrm{diag}\{K_{1_i} < 0\}; \mathbb{K}_2 = \mathrm{diag}\{K_{2_i} < 0\},$$

$$i = \overline{1,3}$$

The analysis of oscillators active damping variants showed advantages of parametric controlling by stiff and dissipative EDE properties . The synthesis task of t-optimal control by oscillator stiffness has been solved using Pontrjagin's maximum principle and logical addition method. It is proposed to use a control magnetic liquid damping unit (MLDU). The main advantages of this units are the small time constant and ability to function in some regimes. When MLDU is used the α_Σ EDE damping ratio is a sum of α_1 component due to the natural and additional passive MLDU damping and α_2 component due to construction stiff control effect. To evaluate the potential possibilities of this type systems following relationships can be used:

$$\alpha_1 = (\mathbf{b}'_o + \mathbf{b}_1) + (-\mathbf{b}_1 + \mathbf{b}_2)\Delta\tau/(\Delta\nu + \Delta\tau);$$

$$\alpha_2 = -0{,}5\ \xi\ \Omega_{min}/(\Delta\nu + \Delta\tau);$$

$\mathbf{b}'_o = \mathbf{a}_o/\omega_{max}$; $\mathbf{b}_1 = \mathbf{a}_1/\omega_{max}$; $\mathbf{b}_2 = \mathbf{a}_2/\omega_{max}$ - are relative coefficients of amplitude decreasing due to the natural and additional damping at minimum and maximum construction frequencies when control unit is used respectively

$$\Delta\nu = \sqrt{\mu}(\pi - \theta); \ \Delta\tau = \pi/2 - \operatorname{arctg}[\eta/\sqrt{\mu}];$$

$$\eta = (\mathbf{b}_1 - \mathbf{b}_2)/\Omega_{max} + \operatorname{ctg}\theta; \ \mu = [\Omega_{min}/\Omega_{max}]^2;$$

$$\xi = \ln[\mu\sin\theta^2 + ((\mathbf{b}_2 - \mathbf{b}_1)\sin\theta/\Omega_{max} - \cos\theta)]^2;$$

$$\Omega_{min} = [\varkappa - \mathbf{b}_{o_{min}}^2/4]^2; \quad \Omega_{max} = [1-(\mathbf{b}'_o + \mathbf{b}_1)^2]^{1/2}$$

$$\varkappa = (\omega_{min}/\omega_{max})^2; \omega_{max} = 2\pi f_{max}; \omega_{min} = 2\pi f_{min} -$$

are minimum and maximum circular frequencies of EDE oscillations; $\theta \in (0,\pi]$-is the parameter determining logic of stiff control algorithm functioning and selected according to condition $\max_{\theta \in (0,\pi]} \alpha_\Sigma(\theta)$.

2.4.The software characteristic

The software of the developed modeling complex is oriented to utilization of personal computers. It have main menu and graphic presentation results menu. Programm tools permit:

- to shape the SSES design arrangement diagram computing its dynamic characteristic in accordance to the selected type of SB (planar or concentrating) and APA emission mode (continuous or impulsive);
- to form the PAMCS structure based on assigned set of type and parameters of sensors, actuators and control laws;
- to investigate the SSES dynamics at three dimensional angular motion taking into account neither more of 50 oscillator modes;
- to evaluate the quality of SB energy pick off and delivery of microwave energy to rectenna at SSES angular motion transient and stationar modes taking into account the mentioned above kindes of solar power receiving and microwave energy transmission.

3. THE SIMULATION RESULTS

Effectiveness evaluation of proposed approach was done using the developed programm-modeling complex by simultaneuos mathematical modeling of body angular controlled motion and relative (oscillative) dynamics of SSES SB panels and APA,and besides receiption,transformation and transmission processes to users of corresponding energy fluxes.The analysis of simulation results shows that ignoring information about EDE current state in the SSES body angular stabilization control law leads to prolongated transient processes decreasing SSES function effectiveness. First of it is due to low damping properties (relative to EDE dynamics) of this control type.Using SB panels of concentration type this fact is especially stressed.

Using information about EDE current state (information about dynamic of so called "generalized" oscillators in particular)in the control law allows us not only to increase the damping control possibilities (and as a result to decreas more than two time the stabilization processes duration) , but to increase PAMCS economical operation.However practical realization of this control type meets definite difficulties due to the problems of information supply. Because of this, a variants of multiloop PAMCS, including a standart central control circuit and local circuit controlling the EDE active damping oscillations, using their stiff charecteristics optimal control was considered. For example it is showed in experiment that when $f_{min} = 1$ Hz , $f_{max} = 1.3$ Hz ($\varkappa = 0.64$),and

$a_0 = 0.016\ s^{-1}$; $a_1 = 0.034\ s^{-1}$; $a_2 = 0.264\ s^{-1}$,

by means of optimal selected θ it may be possible to inrease over 2.5 times the EDE dissipative properties.

The final choice of PAMCS technical realization suggests the period of detailed developments of SSES designe-arrangrment scheme.

The basic problem of experimental of investigation was also determining the PAMCS structure and algoritmic composition, providing competitivness SB with SRC over SB of planar type. As a result of experiments it was found that in case of comparable SB of both types in mass,overall dimensions and specific energy characteristics there is a possibility to provide such a SC orientation quality to the Sun when SB with SRC become competitive already at the period of one year active object functioning and more. It is explaned by lower degradation coefficient SB with SRC compared to planar SB.

Relative energy pick off coefficients dependences for SB with SRC and planar type on the active object functioning period for different PAMCS construction variants are given in Fig.5,6.

CONCLUSION

To solve the multidisciplinary problem of SSES image formation it is proposed the complexation method of the main its subsystems. The modeling environment for realization of complexation procedure is presented as an analitic technique for solving structural parametric synthesis task in an optimizational statement on the base of the SSES complex economic effectiveness criterion . During approbation of this method it has been shown that the complexation can be realizied only by means of developing of nontraditional approaches providing an energetic and dynamic compatibility of main SSES subsystems.On this investigation stage it is found that the using of this tools and mathematic support permits for example to enlarge the advantegeous application area of concentration type SB and to provide its competitivness even at comparetivly short time of SSES functioning .

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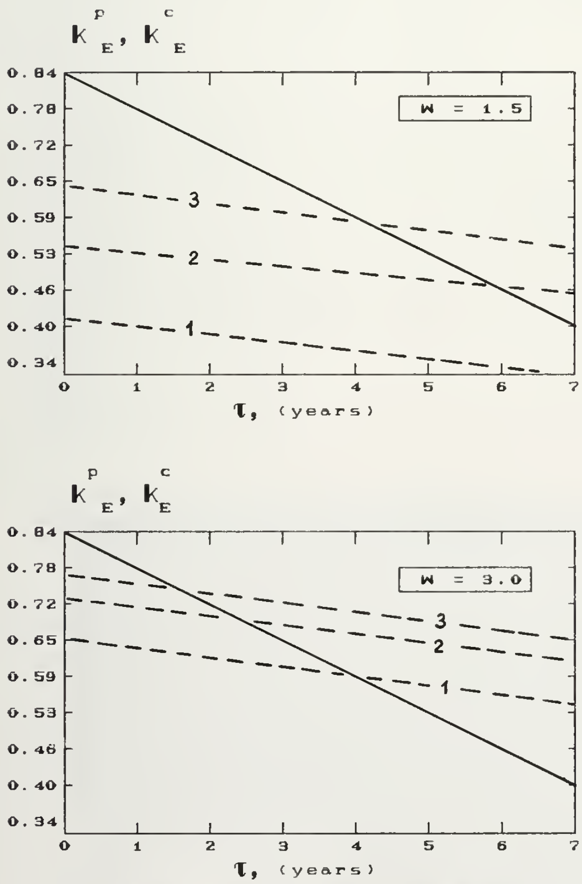

Fig.5. Dependences of relative energy pick off coefficients k_E^c (——) k_E^p (----) on SSES active functioning period when control loops use:

1- optimal position and rate control;
2- optimal control according to extended state vector;
3- control with compensating components;
(local active damping loop is absent).

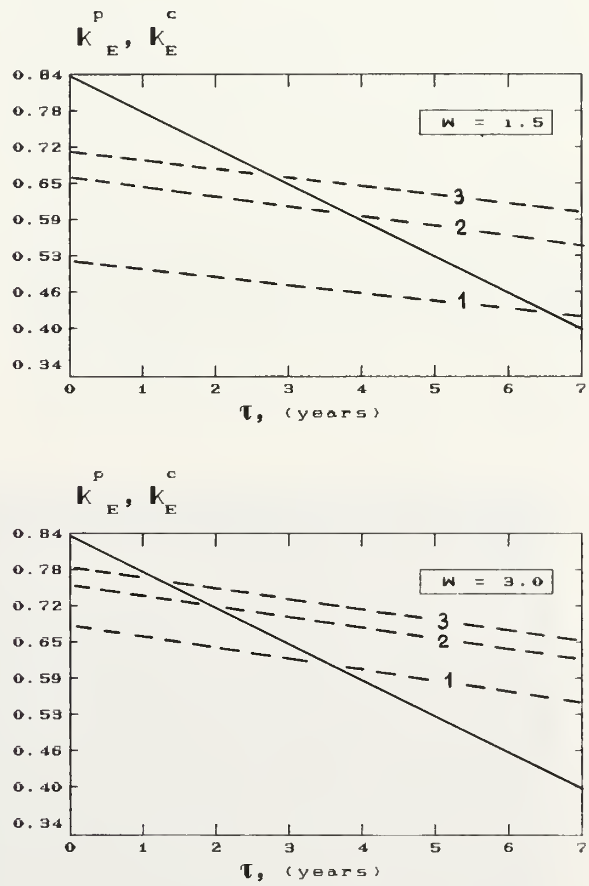

Fig.6. Dependences of relative energy pick off coefficients k_E^c (——) k_E^p (----) on SSES active functioning period when control loops use:

1- optimal position and rate control;
2- optimal control according to extended state vector;
3- control with compensating components;
(local active damping loop is present).

A6.5 SPGD: A central power system for space

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ABSTRACT

This paper describes the Space Power Generation and Distribution (SPGD) concept for providing power to any satellite in earth orbit via power beaming. Other applications such as providing power for terrestrial or space exploration purposes are identified. An assessment of SPGD versus conventional space power is summarized concluding SPGD appears extremely attractive for our space future.

RESUME

Cet exposé décrit le concept de la Génération et Distribution d'Energie d'Espace (SPGD) qui fourniraient l'énergie à un satellite quelconque à défilement autour de la Terre au moyen d'un rayon d'énergie. D'autres applications, telles que l'énergie pour l'exploration spatiale ou terrestre, sont identifiées. Puis, on compare le SPGD à l'énergie spatiale conventionnelle en arrivant à la conclusion que le SPGD semble extrêmement utile pour l'avenir de la recherche spatiale.

I. INTRODUCTION

The availability of adequate supplies of low-cost energy in space will determine the extent to which mankind can reap the benefits of space. Space power today is where earth power was a hundred years ago. In space, each satellite carries its own power supply. On earth a hundred years ago, each farm, home, and business provided its own power. Then in the early 1900s, central electric power generation began, and the farms and cities tied into the grid. Perhaps in space it is now time to tie into the grid.

The Space Power Generation and Distribution (SPGD) concept provides the central electric power generation and transmission system needed to power our space activities for the twenty-first century and beyond. The Pacific Northwest Laboratory,[1] with the assistance of the National Aeronautics and Space Administration, other government agencies and industry, has been developing the SPGD concept since 1988.

II. THE NEED

Currently, most satellites are solar powered. Those in low earth orbit (LEO) generally rely on batteries to supply their power when they are in the earth's shadow. This means the solar panels must be double sized to provide both operational power when they are in sunlight and power to recharge their batteries. In addition, the panels must be even larger to provide the capacity needed to make up for solar cell degradation over the satellite lifetime.

Panel size creates another problem--drag. Reboost capability, in the form of chemical propellants and thrusters, is needed to prevent premature reentry and loss of the satellite. The result is a heavy system with batteries and reboost propellant generally the biggest contributors. The power supply system is frequently 20-30 percent of the total satellite weight. In addition to the weight problem, satellite lifetimes are limited either by battery lifetime from charge/discharge or by propellant inventory.

Perhaps the biggest problem resulting from our current approach to powering LEO satellites is the impact this has on satellite designers. They must arrive at a design that balances satellite capability with the weight and associated launch and other costs of the power system. Frequently, they will start with an assumption of maximum power availability and then adapt the satellite capabilities to the assumed power.

Wouldn't it be interesting to see what satellite designers could do if they didn't have to worry about power? What if all they had to do was "plug their satellite into a wall socket" and their power demands were met? In effect, SPGD provides that "wall socket."

III. THE SPGD CONCEPT

SPGD involves a constellation of power satellites positioned in high earth orbit such that they provide global coverage of power to any satellite in earth orbit via power beaming. Where now the sun's energy, God's power beaming concept, is only available part-

time to LEO satellites, with SPGD there is always a "sun" available.

In our studies we have established a reference SPGD system to compare against current methods of providing satellite power. Shown in Figure 1, our reference system involves twelve 1 MWe power satellites. Each power satellite provides power to multiple user satellites via lasers. The power satellites are positioned above the Van Allen belt and below geosynchronous orbit (GEO). We believe GEO is important "real estate" and should be held for satellites requiring a synchronous orbit.

The 12 power satellites can feed 100 or more user satellites of the size expected in the early 21st century. Twenty percent excess capacity is assumed so that loss of one or two power satellites can be accommodated until replacements can be moved into position.

An overall system efficiency of at least 20 percent appears reasonable by the early 2000s based on current technology development. Efficiency is defined as electricity into the laser to electricity on board the user satellite. It does not include the efficiency of the electric power generation source on the power satellite itself. This reference SPGD system is described in more detail below.

Reference Power Satellite

Our reference power satellite, shown in Figure 2, is powered by a 1 MWe class SP-100 nuclear power system. We selected this system based on the development program currently underway in the United States. The SP-100 program is focused on having a flight ready system around the turn of the century, which is compatible with our proposed SPGD schedule. However, we recognize a 1 MWe SP-100 is pushing the upper power limits of the current SP-100 design, a 100 KWe unit.

Our reference transmitter is a phased array of AlGaAs semiconductor, diode lasers. This laser system was selected because it is compact and lightweight, it provides continuous operation and, most important, it is naturally tuned to a GaAs photovoltaic receiver system enabling high system efficiency. As in the case of the 1 MWe SP-100 power system, the development of this laser transmission system appears reasonable by the early 2000s based on the state-of-the-art today.

In our reference constellation we assumed the power satellites orbit at 20,000 km and the maximum transmission distance would be 28,000 km. Based on a laser wavelength of about 800 nanometers and a receiver collection efficiency of 85 percent (the energy in the main lobe of a Gaussian beam), the transmitter diameter would be 7.5 m.

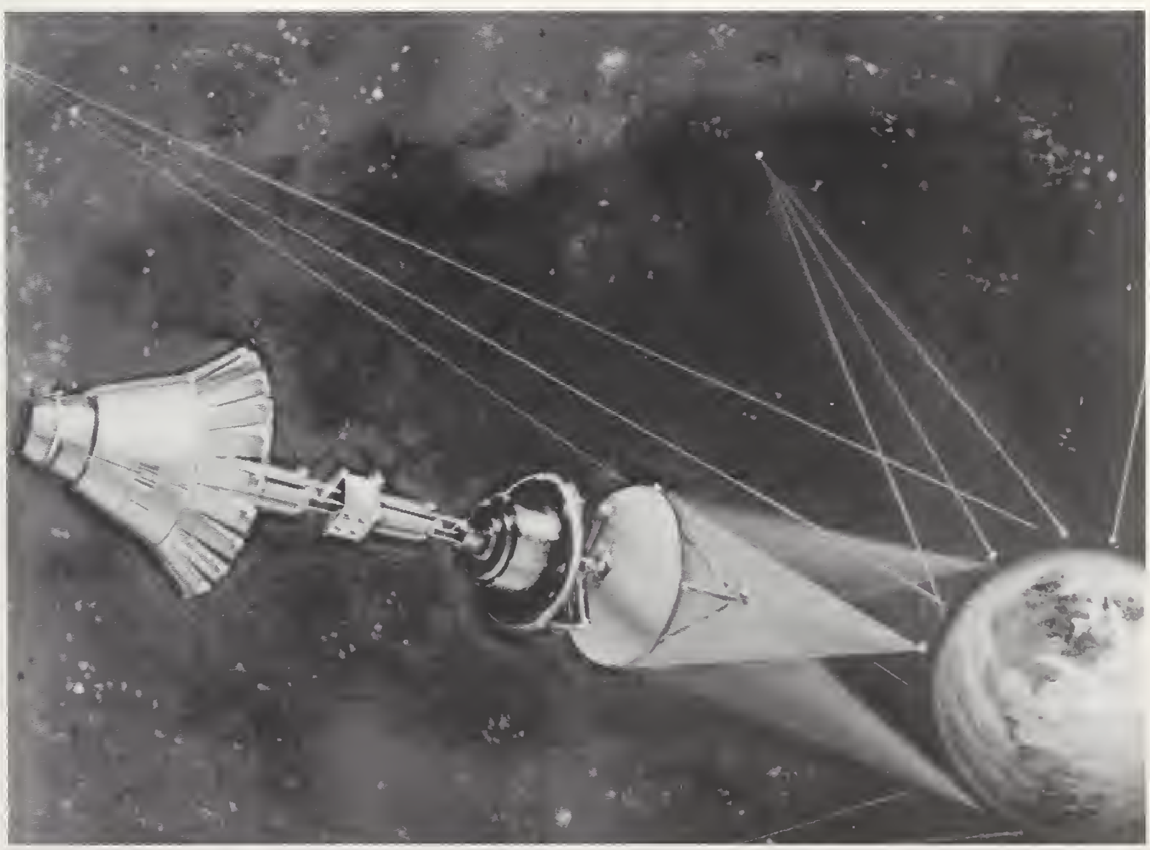

Figure 1. SPGD Reference Concept

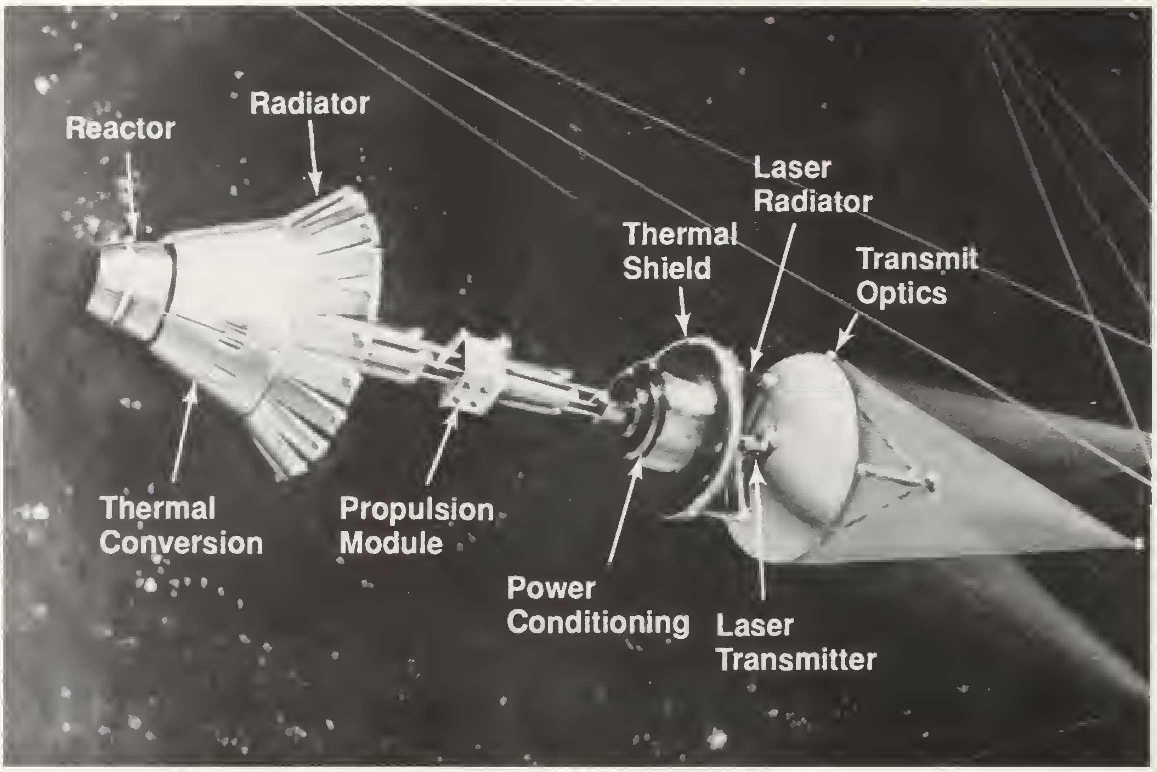

Figure 2. SPGD Power Satellite

Reference Receiver

Our reference receiver is a GaAs "solar" photovoltaic receiver 7.5 m in diameter, the same size as the transmitter. By comparison to a normal solar photovoltaic system, the GaAs cells would be tuned to the laser transmitter frequency rather than the spectrum of frequencies from the sun. This provides the high efficiency needed for power beaming.

We further assumed the receiver would be passively cooled. The upper limit on receiver power capability is based on receiver material temperatures. This receiver would be able to generate up to 130 KWe, and the maximum transmission power intensity would be the equivalent of about 3.5 suns.

System Efficiency

An overall system efficiency of at least 20 percent appears reasonable by the early 2000s. This efficiency is calculated as shown in Table 1.

Table 1. SPGD System Efficiency

Component	Efficiency (%)
Laser	50
Optics	80
Receiver Collection	85
Receiver	60
Total System	20

SPGD Concept Options

We have identified a number of options to the reference SPGD concept. So far there has been little time to explore them in detail. Many of them need more study before a final decision on the specific approach to be used for SPGD. For example:

1) Solar power could be used on the power satellite rather than the reference nuclear system. Perhaps the initial satellites deployed in the 2005-2010 time frame should be solar powered, and the higher power growth system needed for later decades should be nuclear.

2) Ground-based lasers with relay mirrors in space could be used in place of the power satellites.

3) Space-based lasers other than the reference AlGaAs lasers may be preferable, although no serious contenders have been identified as yet.

4) Microwave rather than laser transmission has been proposed. So far microwave transmission does not appear attractive for the transmission distances proposed due to the size of the transmitter and receiver apertures required.

Another option that deserves more study is the option of providing power for selected terrestrial applications in addition to powering user satellites. If SPGD can be justified on providing power in space, additional terrestrial applications may become very attractive.

IV. SPGD APPLICATIONS

The SPGD concept could power any satellite in earth orbit, although satellites in LEO would probably benefit the most. GEO satellites don't have as great a problem with earth-shadows and the attendant weight disadvantages of LEO satellites.

One of the biggest beneficiaries would be Space Station Freedom shown in Figure 3. It is due to be operational in the late 1990s or early 2000s. If SPGD were available, the size of the solar panels could be reduced by 75% and the available power would be nearly doubled.

Another major application for SPGD is powering orbital transfer vehicles (OTV) -- "tugboats in space." Beaming power to an OTV for highly efficient electric propulsion could reduce LEO to GEO costs by 50 percent ore more compared to on-board propulsion systems. And, once the OTV drops off its satellite or other cargo in GEO, it can return to LEO for another load. Or, the OTV could recover problem satellites from GEO and return them to LEO for repairs. A beam powered OTV has about an 80 percent payload capability. Without power beaming, the OTV payload would be 25 percent or less.

SPGD and the power beaming technology developed is also directly applicable to the United States' Space Exploration Initiative (SEI): the colonization of the Moon and a manned mission to Mars. As shown in Figure 4, power beaming could be used to provide power for surface operations, particularly if electric propulsion is used to transport cargo and crews to the Moon or Mars. The electrical supply serves a dual purpose by powering transmitters from lunar/Mars orbit to the surface. Power beaming has an added advantage compared to surface power systems. It can provide abundant power wherever it is needed on the surface, even at locations remote from the home base. Power beaming can also be used to power ascent/descent vehicle orbital maneuvers and earth-lunar transport vehicles.

V. THE BENEFITS OF SPGD

We completed an assessment of the reference SPGD concept by comparing it against current approaches to providing satellite power. Our assessment primarily compared SPGD versus current on-board solar power technology. The major criteria we used for comparison purposes were safety, economics, reliability, flexibility, acceptability and feasibility. Due to the limited nature of the study, we made no attempt to be quantitative except in the area of economics. Even there, the results are tentative. A brief summary of our conclusions is described below.

Safety

In this area we compared the SPGD reference concept, which utilizes a reactor power source, to satellites with on-board nuclear reactors. If SPGD power satellites use a solar power source and are compared against on-

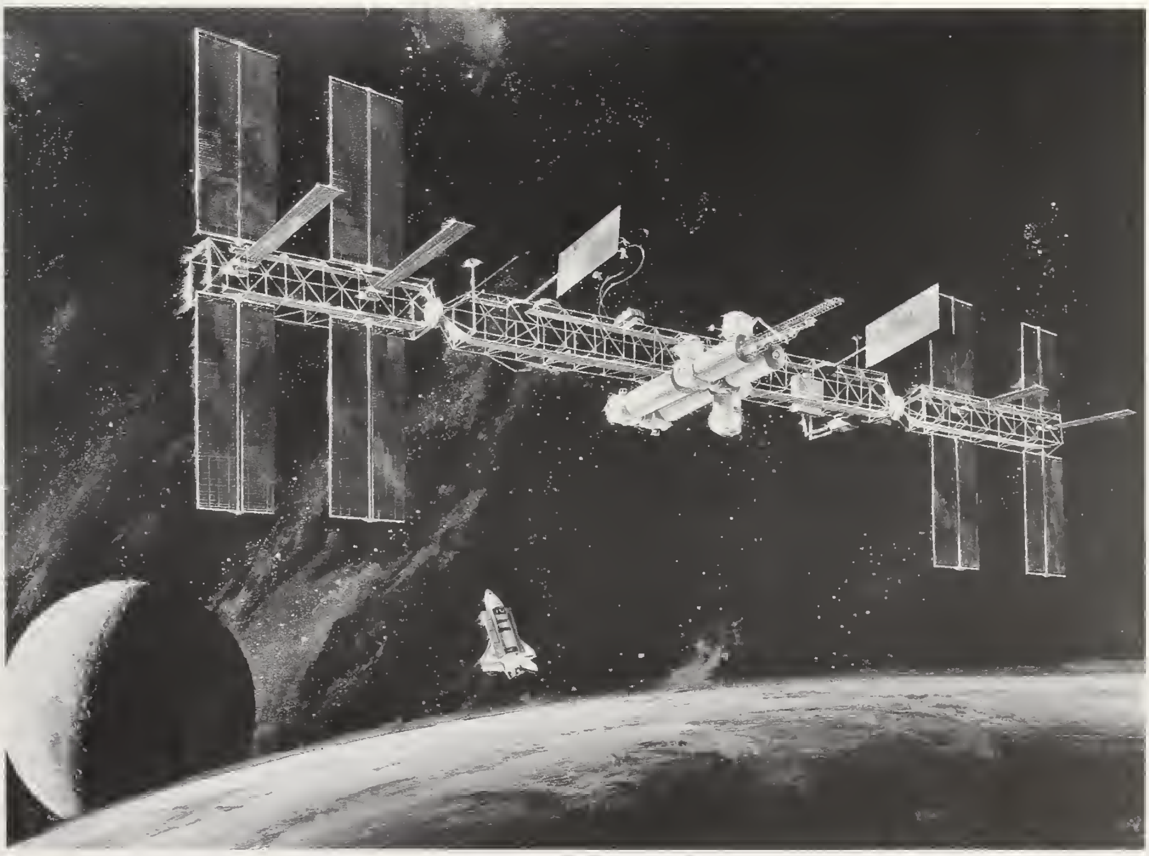

Figure 3. Space Station Freedom

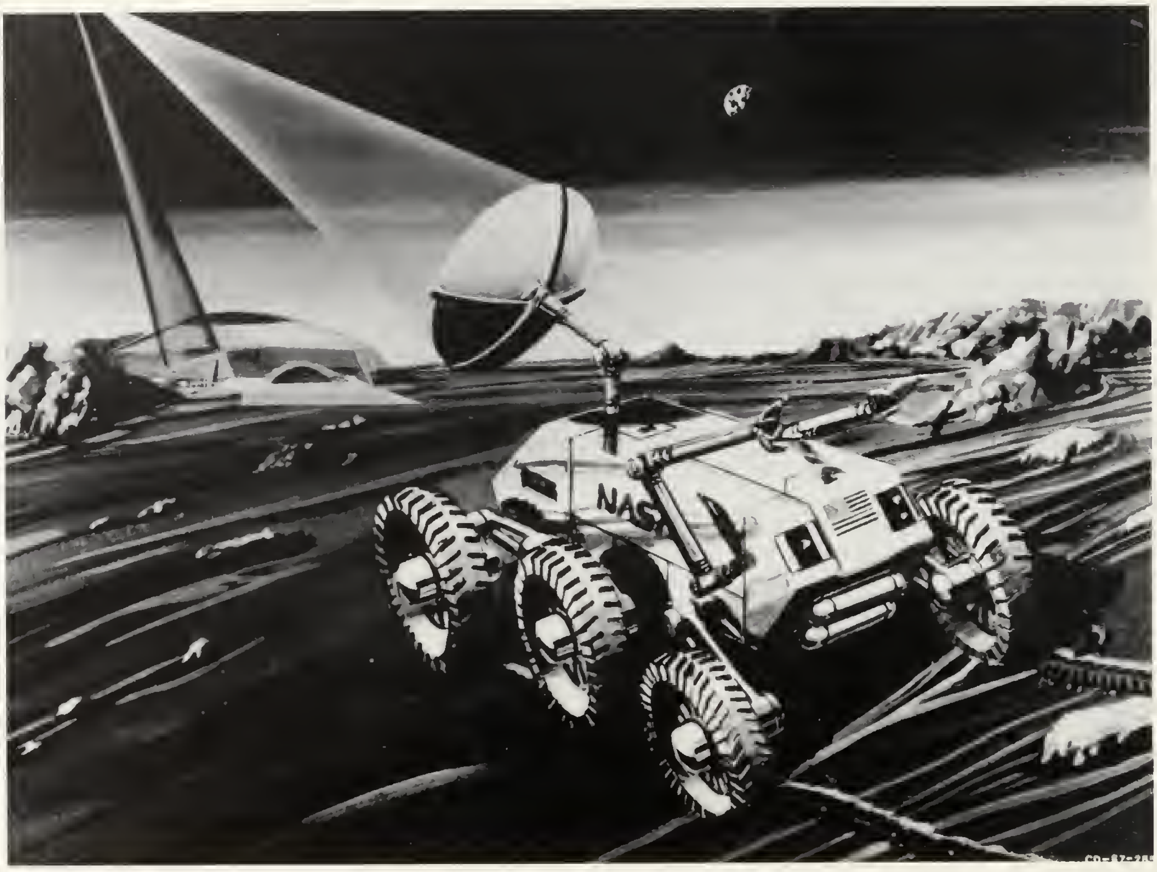

Figure 4. Power Beaming to Moon/Mars

board solar, there would be no particular safety advantage one way or the other. An exception is the laser issue discussed below.

Compared with on-board reactors, SPGD has several major advantages. First, the SPGD power satellites operate only at high-earth orbit; 20,000 km is assumed. This is a 100,000+ year orbit, virtually eliminating any concern over reentry into the earth's atmosphere and potential contamination of populated areas. Inadvertent reentry is probably the biggest single concern regarding the use of reactors in space.

Second, SPGD eliminates the need for reactors on manned space platforms. Concern over radiation exposure of the crew is eliminated. Finally, SPGD requires fewer, albeit larger, power sources than a space architecture using multiple, different-sized on-board reactors to meet the diverse power requirements of future satellites.

On the other hand, there is a potential safety concern with the use of lasers. SPGD lasers are not a problem to the human body as the intensity is only about 3.5 suns. But the laser frequency is such that it could cause eye damage.

In space, eye damage is not a problem because manned vehicle windows and astronaut visors protect against this laser frequency. But if the laser penetrated the earth's atmosphere, and there are windows in the frequency range proposed, the exposure to the eyes of a person staring in that direction could exceed U.S. regulatory limits. The system needs to be designed to operate at a frequency which is attenuated by the atmosphere and/or the lasers should be pointed only tangentially to the earth.

Economics

There are a number of economic advantages for SPGD making it economically attractive.

1) The total system mass is about half that of solar for satellites in LEO, and weight is costly. Currently U.S. launch costs are about $9,900/kg (U.S.). The big weight drivers for solar are batteries and reboost propellant.

2) With SPGD, LEO to GEO orbital transfer costs are cut in half. SPGD enables an orbital transfer vehicle with 80 percent payload capacity, and this OTV has multiple round trip capability. It appears that SPGD can be justified on OTV capability alone. Anything else is "free".

3) User satellite costs are reduced as on-board power supply requirements are minimized. The power system generally constitutes 20-30 percent of the total satellite weight.

4) User satellite lifetimes can be extended. Battery lifetime is no longer a problem. Also, reboost propellant inventories are minimized as efficient electric thrusters can be used.

In comparison with on-board reactors, SPGD has a significant cost advantage. SPGD uses a standardized design where on-board systems require specialty designs.

The one cost disadvantage of SPGD is the high capital cost of the reactor system. We assume the cost of one power satellite including launch and deployment in a 20,000 km orbit is $850 million (U.S.). Use of standardized systems may reduce these costs. Or, solar powered SPGD satellites may be attractive based on cost. Clearly, this is an area needing more study.

Reliability

SPGD has significant reliability advantages over on-board systems:

1) There is redundancy in the system. If one power satellite fails, others can pick up the load.

2) There is excess receiver capacity in the event of partial loss due to degradation or damage.

3) A standardized SPGD system design should result in higher reliability compared to specially designed on-board nuclear systems.

4) If all else fails, the receiver can get energy from the sun.

5) With an OTV system enabled by SPGD, malfunctioning satellites can be recovered and fixed.

The one disadvantage is the need to replace a power satellite if one fails. But there is time for replacement as a result of the excess capacity built into the system, so this is not really a reliability problem.

Flexibility

Probably the biggest benefit of SPGD is the flexibility it provides user satellite designers:

1) It can feed any satellite in earth orbit regardless of power requirement or location.

2) It can augment existing solar powered satellites by beaming power to the existing solar panels.

3) It permits satellite designers to optimize their designs based on mission requirements and not worry about the amount of power required or the design of the power system.

4) SPGD enables increasing user satellite power if requirements change during the course of the mission.

5) SPGD enables use of efficient electric thrusters on a user satellite to change orbits during a mission.

6) The power satellites can serve as navigation and communication links with other satellites in earth orbit.

7) SPGD may be able to beam power for selected terrestrial applications in addition to providing power in space.

We found no significant flexibility disadvantages with SPGD.

Acceptability

There are some significant advantages for SPGD in the area of acceptability:

1) SPGD frees mission planners from power concerns making it more acceptable from their vantage point.

2) SPGD isolates users from any concern with the use of nuclear power.

3) The orbital height of the power satellite essentially eliminates reentry concerns with the use of nuclear reactors in space.

4) SPGD keeps nuclear reactors off manned satellites in earth orbit.

5) The power beaming technology can be used to enhance lunar and Mars exploration missions.

The one drawback to SPGD from an acceptability standpoint is that it changes the way we provide power in space. Change and the transition involved can be difficult for some people and institutions to accept.

Feasibility

The SPGD concept appears to be technically feasible. We have identified no "showstoppers". The major advantages are:

1) SPGD is based on existing or currently developing technology. The reactor is based on the SP-100 design. Pointing and tracking is compatible with existing space technology, as is command and control. GaAs receiver and AlGaAs laser technologies are being developed.

2) User satellite design is simplified by eliminating much of the existing power system.

3) Standardized reactor power system and receiver designs will be easier to develop than the specialty designs now required.

Even though SPGD appears feasible there are major development efforts required, particularly the development of higher power reactors and laser transmission systems.

Conclusions

The Space Power Generation and Distribution concept appears to solve many of the current energy problems in space. Instead of being constrained by the limitations of current on-board power systems, satellites and missions can be designed for a power-rich environment. Orbital transfer vehicles can become a reality reducing the costs and investment risks of satellite operations.

SPGD can readily pay for itself in powering satellites in earth orbit. If it can provide power for selected terrestrial

applications, it becomes that much more attractive. And if we develop the technology for earth orbit, it is readily transportable for Moon and Mars applications.

In summary, we need a "central power system in space" to move forward into the twenty-first century!

REFERENCE

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A7.1 A research program for the planning of energy transmission systems through microwave beams, and evaluation of the related environmental impact

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Abstract

The possible applications are analyzed of microwave-energy transmission systems and the planning of a research is proposed which, starting from general considerations on the world's energy requirements and the state of the art of available manufacturing technologies, allows the identification of the criteria for the dimensioning of a demonstration plant.

The proposal is particularly finalized to the dimensioning of high power plants for energy transmission through microwave beams, suitably designed to operate in full respect of human health and environment, and to the solution of electromagnetic compatibility problems.

Résumé

Ce rapport analyse les applications possibles de la transmission d'énergie par microondes et propose un projet de recherches qui, après quelques considérations générales sur les besoins d'énergie et les disponibilités hydro-électriques aussi bien que les possibilités offertes par les technologies les plus actuelles, permet d'établir les critères pour la mise au point du projet et les dimensions d'une installation expérimentale. La proposition vise en particulier à établir les dimensions d'une installation pour la transmission d'énergie par microondes qui soit adaptée à opérer dans le respect de l'environnement, de la santé et considérant les solutions aux problèmes de compatibilité électromagnétique posés.

General Considerations for the Coverage of Energy Requirements in the Long Term.

The coverage of enersy requirements in the long term is an old-dated issue, and the different facets of the problem have had a substantial evolution in time.

It is hereby reminded that the four UN Conferences for the peaceful uses of nuclear energy, held in Geneva between 1955 and 1971, were triggered by the urgent need of long-term saving of non-renewable energy resources, i.e. fossil fuels, which cannot be dispensed-with, as oil for transports.

The main subject was electric energy, as it is the vector through which all primary sources can be transformed into and then used in a variety of applications.

While it is true that the search since those years has brought the discovery of new deposits, particularly oil and natural gas, their reserves being in any case guaranteed for only half-century, the environmental problems call for an urgent retreat from the use of fossil fuels, first of all coal which is the major factor in the greenhouse effect.

It is unanimous the conviction by which the top priority belongs to energy-savings in all the sectors, but this is not enough as this "virtual resource" is eventually destined to exhaustion, when all energy economies will be saturated under the thrust of cost-increases. And then, as energy is a fundamental factor of growth , the rate of increase of consumption will again grow. Even if there were a saturation in the demand of electrical power, which is to be proved, nevertheless the problem of exhaustion remains, even if delayed. It is hereby reminded that the assessment of the duration of energy reserves is usually done on a constant consumption basis.

The solution to these problems, as concerns electric energy, points to the following possible paths:

- Fusion of Hydrogen Isotopes. This solution will not be available sooner than the first half of the 21st Century.

- Nuclear Energy by Super Self-Breeding Reactors. These are the subject of vast-scale industrial experimentation.

- Exploitation of solar energy by space stations in geo-stationary orbits and transmission to Earth by microwave beams.

- Full exploitation of hydroelectric resources and transmission to industrial centers by intercontinental microwave transmission.

The latter form is that which deserves most attention, taking into consideration the possibility of an intercontinental transmission of energy from the mentioned resources, by realizing a satellite link analogous to data and broadcast transmission .
This idea moves from the assumption that the realization of such a project could be the first step, and allow the next step, which would be the construction of huge orbiting solar power stations.

The "proposal of a program of study and research on the possibility of intercontinental energy transmission via satellite" has been the subject of a paper presented at the "Journées d' étude sur les centrales Solaires Spatiales: état de l'art" [1]. Reference is made to such paper for the contents of the proposal while in this paper the important issue concerning microwave energy transmission is reexamined.

In this case the exploitation of such mean concerns the transmission between sight points on the Earth's surface.
The problem concerns particularly the transmission between islands and the continental shelf, at distances such as 50 or 60 Km, and more for elevated sites.
The transmission by submarine cables is today very expensive, particularly for small powers-as is the case for an island-owing to the measures to be taken against trawling, when cables are hooked and broken. Secondly, there is the cost of conversion from AC to DC and viceversa, in case the distance exceeds some tens Km and the voltage exceeds 100 kV.
Some applications which require comparison with cables are, for instance, energy transmission between California and coastal islands, the Hawaii archipelago, the Philippines, many islands in the Mediterranean Sea, etc.

There is obviously an environmental question tied to the use of microwaves, which requires an accurate analysis, as it finally deems the microwave-energy transmission system as suitable or not. Health problems are the primary concern for such analysis [2].
It is hereby proposed an experimental program of microwave energy transmission from sight points on the Earth's surface, such as an island and the coast, to record all the data required for the feasibility and cost-effectiveness of the project, all in the view of a solid application, even if on a small industrial scale.

Selection of Application and Planning of the Activities for the Feasibility of a Demonstration Plant.

The main applications of microwave-energy transmission can be summarized as follows:

- Transmission from point to point on sight on the Earth's Surface.
- Transmission from point to point in Space.
- Transmission from Space Platform to the Earth's Surface (SPS), and viceversa (airborne or space platform powered from Earth).
- Transmission over the continents by reflector satellite.

Among these applications, the optimal choice for conducting a feasibility study allowing the acquisition of the basic know-how for the feasibility of a small power demonstration plant (order of hundreds of kW) is an application for:

- Point to point on Earth (e.g. island link, Fig. 1).
- Point to point in Space (e.g. satellite link, Fig. 2).

This is the first step to consider for the definition of the specifications of the demonstration plant.

The second step is to identify a plant of such dimensions to allow experiments of environmental and health impact, in view also of future applications of transmission over the continents by reflector satellite.
In all these cases the delicate aspects of human health take considerable importance, as well as those of e.m. compatibility and impact on the atmosphere and, last but not least, the aspects of attenuation on paths in case of beam directions not perpendicular to the Earth's Surface (Fig. 3).

A fundamental role for all these applications is that of the selection of frequency, which in case of transmission from point to point in the short range (up to 100 Km) can be increased to values compatible with the state of the art technology.

In particular, the plant will be dimensioned and set in such a way to allow also the powering, with adequate configuration of the transmitting antenna, of a stationary platform at high altitude (Fig. 4).

This allows the dual use of the plant: point to point on earth and earth to point in space. In this second configuration, the stationary platform can monitor, at various altitude levels, the beam-atmosphere interactions in real time.

Some Dimensioning Criteria of the Plant.

With regards to the aspects of the optimal dimensions of the demonstration plant, two main links can be designed in the different frequency ranges 2.45 GHz and 30 GHz in order to test, in real working conditions, the behaviour at the extremities of the allowed frequency range.
In the case of the stationary platform the two signals can be used alternatively to transmit the power or to control the platform position.

Considering an average transmitted power density of 200 W/m^2, an antenna transmitting 100 kW could be obtained with linear dimensions in the order of ten meters. Such a structure could be easily moved to test the system transmission both to a ground station, and to a suspended platform. Two sets of magnetrons working at the two different frequencies could be mixed in a unique phase array structure, in order to achieve a simpler cooling system. The number of active components involved in the structure (some hundreds) could allow an amount of working time sufficient to test the system continuously in different meteorological conditions.

More problematic could be the design of the receiving rectenna, because of the very different wavelength involved. We propose two solutions: again a mixed receiving structure (two sets of rectennas, tuned to the two frequencies, in the same plane or in two different planes), or a travelling wave antenna directly deposited on the semiconductor substrate (e.g. amorphous silicon).

With regards to the aspects of environmental impact, the research will be oriented to explore at various power densities the complex mechanisms of interaction between the high-density power microwave beams and the different atmospheric components, developing and validating the propagation models which apply to the concerned energy fields.

The summary of the activities for the study and the realization of the demonstration plan in the proposed research program MICENE (Microwave-Energy) is shown in Fig. 5.

Assessment of Impact on the Atmosphere.

Among the aspects of environmental impact owing to a high power microwave beam, it is well known that those on atmosphere have a very important role. [4], [5].
The problems dealt with in the demonstration plant allow the correlation between the beam and the atmospheric gases which govern the radiation exchanges in the terrestrial atmosphere (mainly CO_2, CH_4, etc.) with important consequences in determining any change in the greenhouse effect.
In this case, the modelling must take into account a series of interactive processes which at this stage are not well known.

To confirm the above, it is important to remind that the unexpected discovery of the hole in the ozone layer has aroused the need of reviewing and extending the theoretical bases and, at the same time, to exploit to the maximum extent the possibilities offered by technology to improve the quality of measurements and extend and enlarge the data-bases for the study of the atmosphere.

The MICENE program would thus allow the incrementation of studies concerning the atmosphere, and contribute to an improved situation of research which today is still lacking quantitatively and qualitatively.
The complementary measures performed with high technology sensors from both the surface and the platform would also be of considerable importance.
The measurements which are most suited to give information on the ionosphere and on the high atmosphere will surely supply data on their chemical components and changes due to particular microwave beams, and on dynamic problems.

Among the measurements made with IR and microwave instruments and MST (Mesosphere - Stratosphere - Troposphere) Radar, it is important to monitor the following parameters (in presence/absence of the microwave beam):

- Column content of Ozone.
- Vertical profile of Ozone.
- Temperature.
- Vertical profiles of ClO and H_2O.
- Profiles and vertical distribution of aerosols and NO_2.
- Column contents of NO_2 and HCl.
- Vertical profiles of CH_4, N_2O, HNO_3, $ClONO_2$, OH.
- Electron density in Ionosphere.

Study of Problems relating to Human Settlements and Electro Magnetic Interference.

While the effects of the microwave radiation field on humans and on the biosphere have been already focussed by a number of studies [2], other important effects need to be studied in parallel to the demonstration plant, in order to complete the information on the environmental impact. They include:

I. Energy penetration in Human Settlements [6] and possible resonance conditions.

II. Electromagnetic Interference (EMI).

These are separately dealt with below:

I. The penetration of energy in human settlements is tied to the nature of the coupling of the incident field with each exposed structure. It is necessary to examine if there can be hot-spots with energy density greater than the incident field. To this end it should be taken into account that each exposed structure has its characteristics, depending on its materials

and dimensions.

Structures can be split in three groups:

1. Civilian Buildings, realized with materials having the characteristics of dissipative dielectrics, with many apertures.

2. Industrial buildings, realized with both conducting materials and dissipative dielectrics.

3. Mobile structures (cars, boats, planes) mainly metallic and with large apertures.

The determination of hot-spots and spatial resonances in the structure is a very complex problem. It is proposed to make simulations, through the hypothesis of a uniform plane wave, normally incident on the radiated structure. The structure is simplified to a geometric solid (cylinder, parallelepiped, spheroid).

Once the field in the structure is obtained, any condition of spatial resonance can be pointed out, together with hot-spots, energy dissipated in dielectrics, reflections by metallic walls.

Theoretical modelling of mobile structures poses great difficulties An useful approach is the experimental method, by exposing scaled structures to a microwave beams and measuring the field inside.

The study should also include the solutions to be adopted in presence of negative effect, i.e. the use of absorbing walls, mode mixers to make uniform internal fields, natural and artificial reflectors to decrease the coupling.

II. EMI problems are a large variety, owing to the diffusion of electronic and telecommunication equipments in civilian, industrial and medical applications.

The main systems concerned can be split in two groups:

1. Transport Systems

a) Radio-aids to aerial, naval and terrestrial navigation,

b) Electronic systems for emergency and alarm,

c) Electronic systems for monitoring and control of vehicles.

2. Public Telecoms

a) Microwaves Telecom Networks,

b) Remote Sensing systems for civil protection and environmental monitoring,

c) Telephone, broadcast, radio-links systems,

d) Space telecommunications.

EMI problems are of relevance as electronic equipment are sensitive to fields as small as 10 mV/m, corresponding to a density of 2.5 x 10^{-7}W/m^2, i.e. 10^{-9} times the beam center density, which at the present Knowlodge is expected to be around 250 W/m^2.
The shape of the microwave beam has its relevance in EMI problems, and also the presence of secondary lobes of the antenna and the area of incidence of the beam.
All these problems are tied to the types of radiating antenna. Another important parameter is the transmission frequency, as a higher frequency allows a finer beam and a reduction of radiated areas.

For this type of problems, protective techniques of the interferred systems can also be studied. Such studies, by the way, have already been conducted on operating systems, using techniques, such as receivers with high noise-rejection input, improved S/N ratio, shielding of the more sensitive components, and finally, noise cancellation by active suppression.

CONCLUSIONS

The "MICENE" research program aims to defining the specifications of a demonstration plant and planning the relevant activities to acquire the basic and common know-how, indispensable for a reliable feasibility study for microwave-energy transmission via reflector satellite.
Among the possible applications of high power

microwave-energy transmission, studied to date, an experimental application is selected, with power sufficiently high to allow:

1) The acquisition of the know-how and the proved feasibility of small power (order of 100 kW) plants for microwave-energy transmission from point to point for applications in space and on Earth, now ready for deployment (particularly in space).

The demonstration plant will have in particular these features:

- To be initially realized only for point to point surface experiments, which are mandatory as feasibility tests, before planning expensive experiments in space which are scarcely reliable owing to the present state of the art of applicable technologies.

- To have dimensions such to overcome health and environmental impact aspects and also e.m. compatibility ones which up to now have been intensively dealt with in theory, but never tackled and exhaustively delved into.

2) The proved feasibility of high power plants (order of GW) for long-range energy transmission, in full respect of health and environmental considerations, and keeping in mind the problems of electromagnetic compatibility.

An important fall out of the "MICENE" program will concern innovative systems for the remote powering of satellites and space stations as well as for the remote fueling of aircrafts.

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FIG. 1 - PHILIPPINE MAIN ISLANDS WITH THEIR PRESENT AND PLANNED ENERGY PRODUCTION AND DISTRIBUTION NETWORK

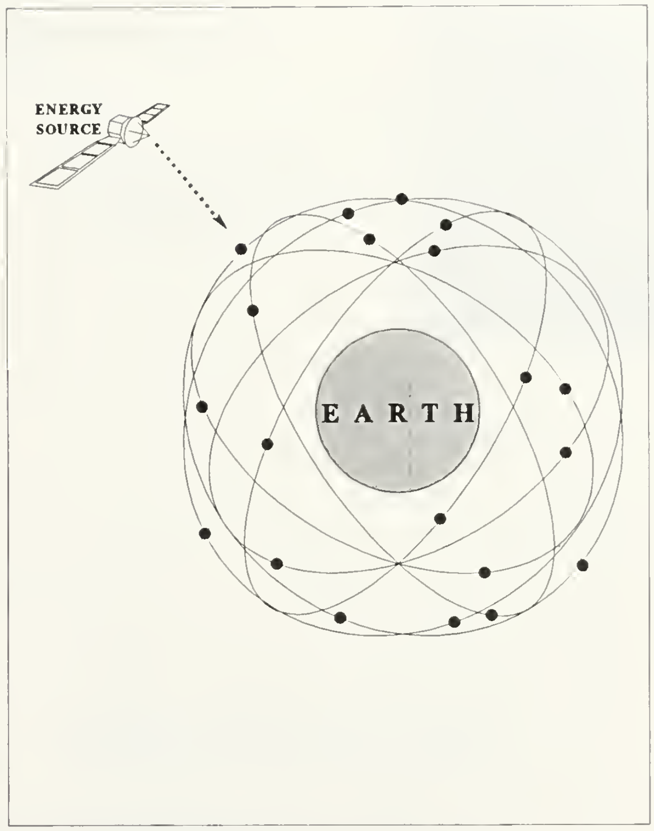

FIG. 2 - POINT TO POINT IN SPACE NETWORK

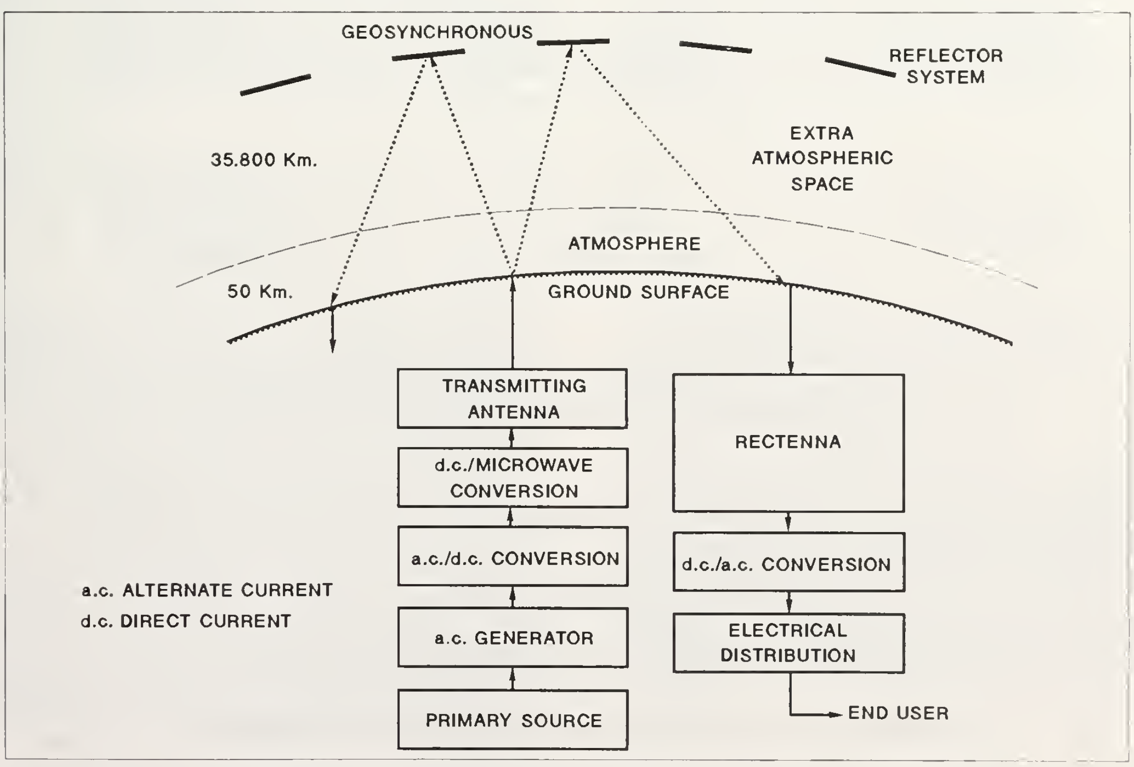

FIG. 3 - REFLECTOR SATELLITE ELECTRIC POWER TRANSMISSION SYSTEM (S.T.S.) BLOCK DIAGRAM

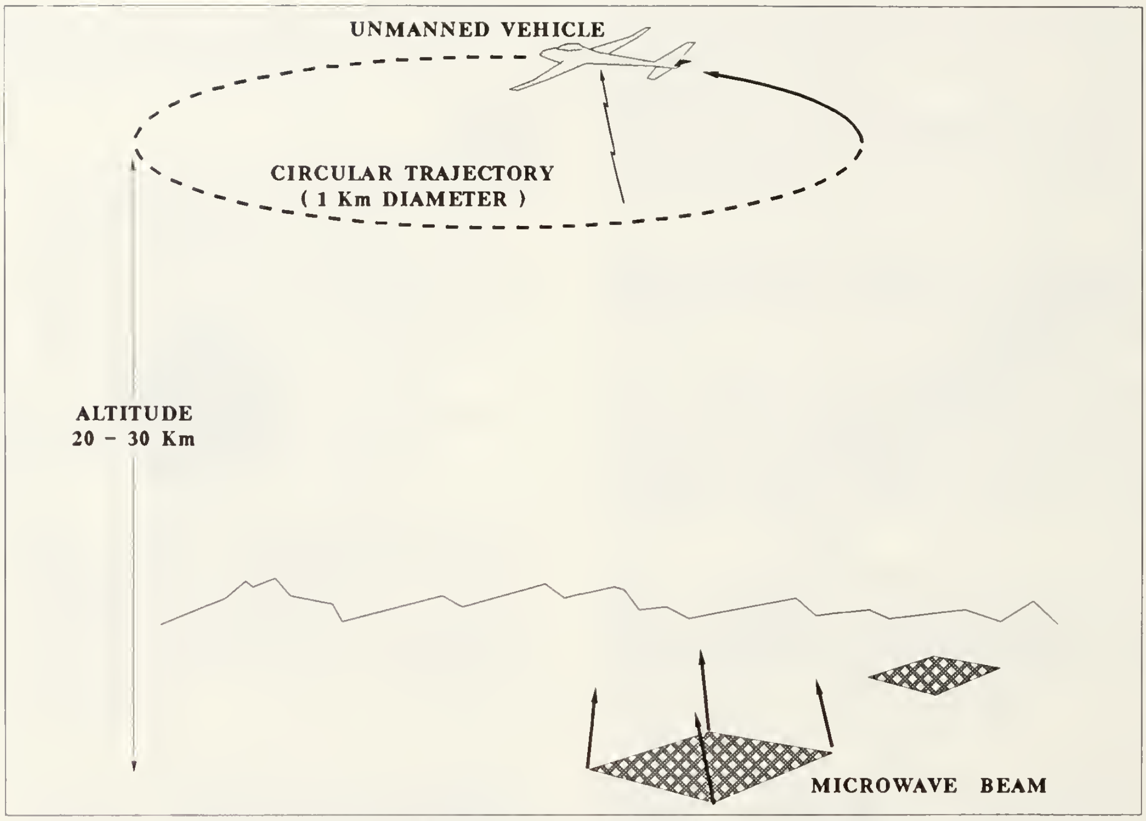

FIG. 4 - HIGH ALTITUDE STATIONARY PLATFORM AND MICROWAVE GROUNDED PLANT

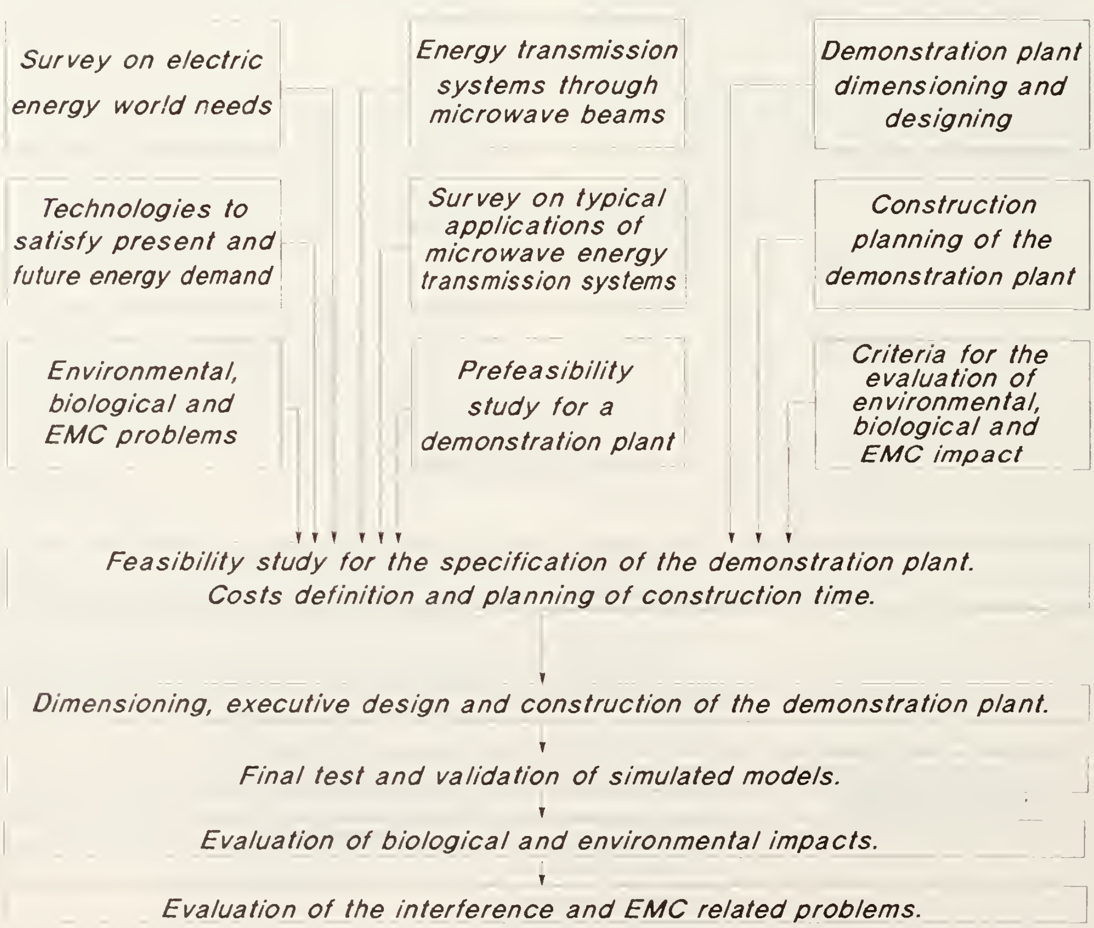

FIG.5 - SUMMARY OF THE ACTIVITIES FOR THE MICENE (MICROWAVE ENERGY) RESEARCH PROGRAM

A7.2 Energy transmission in space: an enabler technology

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Abstract:

This paper is based on a study performed for the European Space Agency by a number of companies and institutions under the leadership of Eurospace.

It summarizes the present status and prospects of the techniques of transmitting electrical energy at a distance in space or between space and the earth and describes the progression to be recommended in the in the experimentations to be performed in space do establish a network of geostationary Space Power Stations (SPS).

The recommended planning would include, as an essential step, the development of relatively small space stations, specialized in the production of electrical energy, and capable to beam this energy to other satellites. It will be seen that such stations could be exploited commercially.

Résumé:

Le papier s'appuie sur les résultats d'une étude conduite pour le compte de l'Agence Spatiale Européenne par plusieurs sociétés et institutions sous la direction d'Eurospace.

On y trouvera un résumé du statut actuel et des perspectives des techniques de transmission à distance d'énergie électrique dans l'espace ou entre l'espace et la terre. On y trouvera également une recommandation concernant le calendrier des expérimentations qui devraient être poursuivies dans l'espace pour préparer un programme de "Space Power Stations" (SPS).

On verra que ce calendrier comporte une étape intéressante, qui est le développement en orbite de stations capables de produire de l'énergie en quantité relativement modeste et de transmettre cette énergie à d'autres satellites. On verra que de telles stations pourraient faire l'objet d'une exploitation commerciale.

0. Introduction

The concept of electrical power transmission by means of electromagnetic wave beams is now around for several years. The concept imagined by P.E. Glaser of using large orbiting stations to collect solar energy on geostationy orbit, transforming it into electricity, then into microwaves and transmitting it to the earth surface to be reconverted into electricity and distributed via the conventional power networks, dates from 1968, and the first experiments beaming electrical power over more than one kilometer by microwaves have started on the Earth surface in 1975.

The Glaser project requires the completion of a number of technological achievements in the fields of space transportation (a reduction by one or two orders of magnitude of the transportation costs to the geostationary orbit seems to be an absolute condition), energy generation, conversion and storage, structural and thermal engineering etc. However the most important and difficult requirement is that long distance transportation of electrical energy, by electromagnetic radiations or other means has to become a feasible and economic technique.

In this paper, we intend to propose a development plan for the establishment of Space Power Stations of the type proposed by Glaser, based on two principles:
the first, that the most critical techniques are those regarding energy transmission;
the second, that the activities proposed in this plan ought to generate revenues as early as possible.

These principles lead, as will be seen, to the natural conclusion that an intermediate objective ought to be proposed before the actual implementation of large solar power stations: the establishment, in space, of relatively modest power stations, capable of beaming electricity to other satellites, what we have called "POWERSATs". We will see that such powersats can be useful, can be realistically envisaged for the first decade of the next century, and could actually bring revenues long before the construction of large geostationary power stations can be envisaged.

1. Transmission Techniques

1.0. Introduction

The first technology that can be envisaged for transmitting electrical power in space is the mechanical connection: this means using a cable or a "plug in" connector for establishing the contact between the electricity generator and the receiver. The "plug in" solution is relatively straightforward. The cable solution seems adapatable for distances of several tens kilometers and is attractive from various viewpoints.

However, the most promising technology is without any doubt the transmission by electromagnetic waves, and in particular:

- the transmission by microwaves or, better, submillimeter waves;
- the transmission by laser beams.

A quick comparison between the use of laser and microwaves can be made as follows.

Power collection efficiency of a uniformly tapered antenna is given by equation (1).

$$e = 1 - J^2(U) \qquad (1)$$

where e = power collection efficiency

r_t = transmitting antenna radius

r_a = receiving antenna radius

λ = transmission wavelength

d = transmission distance.

J_0 = J-type Bessel function

$$U = \frac{2\pi}{\lambda} \cdot \frac{r_a \cdot r_t}{d}$$

For an efficiency of 89% for an uniform taper, or for 96% for an optimally shaped taper, U has been found to be approximately 4, which permits to simplify equation (1) and write, instead:

$$d = \frac{\pi}{2} \cdot \frac{r_a \cdot r_t}{\lambda}$$

(2).

This permits to compute that, with a transmit antenna of 10. m diameter, and a 4. m receiver, a transmission efficiency of 90% can be achieved for distances of approximately:

Table 1

Distances for efficient transmission

0.13 km at 2.45 GHz (12 cm wavelength)
1.3 km at 24.125 GHz (1.2 cm wavelength)
16 km at 300 GHz (1 mm wavelength)
9 800 km for a laser beam at 1.06 micron wavelength
26 000 km for a diode laser beam at 0.6 micron wavelength.

This comparison show the advantage of using high frequencies for obtaining good transmission with reasonable antenna sizes.

Other factors have naturally to be taken into account, such as safety or minimizing radiation pollution, but a priori, submillimeter waves ought to be preferred to centimeter microwaves, and laser beams to microwave and submillimeter microwave beams for transmission efficiency.

However, the technologies are not all in the same status of development and the choices are not as clear-cut as might be expected. The target dates for the exploitation of the systems taken into considerations are constitutes in particular a factor of prime importance.
This will appear in the next paragraphs.

1.1. Microwave and submillimeter waves transmissions

1.1.1. Introduction

Production of microwaves is currently made by using tubes.
However, as in the case of transmissions, where travelling wave tubes are replaced, for some wavebands, by solid state devices, use of solid state devices for the production of energy beams can already be envisaged.

1.1.2. Microwave tubes

Microwave tubes can be classified in several families:

Travelling wave tubes (TWTs)

TWTs associate a long, thin electron beam with a periodic slow-wave structure, not resonant, and sized so that the electron beam interacts with a slow forward electromagnetic wave propagating on the structure.

TWTs are widely used, as is known, for communications, and thus are a mature technique. They could be used for energy transmission. However, because of their low efficiency (of the order of 10 to 20%), they do not seem to represent an optimized choice for power transmission in space.

Klystrons

Multicavity klystron amplifiers are longitudinal interaction tubes, having five or four resonnant cavities, separated from each other by narrow drift tubes. The input cavity is connected to the signal to be amplified, and the output cavity to the useful load. The bandwidth is usually very small.

Typical multicavity klystrons are used for television transmitters (VHF and UHF bands), with powers of the order of 50 kW. and efficiencies comprised between 25 and 35%.

Medium power klystrons amplifiers are used in the continuous mode for medical and scientific applications at operating frequencies comprised betweem 1.3 and 18 GHz, and with output powers of the order of 1 kW.

High power klystrons, with long pulses or even continuous wave operations are being developed for applications such as accelerators and thermonuclear fusion. Such tubes ("Superklystrons") are capable of delivering 1 MW of CW output power with 65-70% efficiency at frequencies of some 350 Mhz.

Gyrotrons

Gyrotrons are revolutionary millimeter-wave vacuum tubes, under development in USA, Western-Europe, USSR and Japan, in particular in the context of the fusion research. They promise to permit the generation of extremely high power levels at mm wave frequencies. Efficiency (DC-RF) figures of the order of 30% have been reached. Higher figures are expected.

Magnetrons

A magnetron is a circular diode, to which is applied a magnetic field parallel to its axis. Oscillations occur when the electrons are given specified values of angular velocity. Several structure are used to obtain oscillations and tuning.

A wide range of magnetrons exist, working in the continuous or the pulsed mode. Continuous wave magnetrons can deliver up to 6 kW of power at 2.45 GHz (for industrial microwave heating), with efficiencies up to 70%.

In the preparation studies for the SPS programmes, it has been envisaged to produce microwave beams by using cheap magnetrons derived from the technology used for microwave ovens. The present state of technology is however still far from this situation. Present high power magnetrons remain expensive equipment, with relatively short operational lives.

Free electron laser (FEL)

Free electron lasers are basically tubes capable of generating beams in the optical regions of the spectrum. They are thus at the border between laser and microwave technologies: they will considered in the laser section.

Conclusion regarding tubes

The technology is mature for ground applications within a certain range of powers and wavelengths.

Power output of the order of several MW can be obtained at the lower frequencies (1 GHz), the power level attainable decreasing as one gets to the highest possible frequencies (of the ordrer of 30 GHz).
Obtaining a klystron capable of 10 - 15 kW at 3 GHz, for example, with efficiencies of the order of 40 to 60% would, in principle, be quite feasible.

For higher power and frequencies, the present limits of pulsed klystrons and the curve given for the gyrotrons give an indication of what can be envisaged for the future.

1.1.3. Solid state elements

Solid state technology means, in particular, the Field Effect Transistors (FETs). Although GaAs FETs are very low power devices, temperature limited to a few tens of watts each, they are inexpensive and can be used in quantities. Low powers (a few hundred watts) constitute the priviledged field of solid state, but the area for competition extends to power outputs of several tens of kilowatts.

1.1.4. Beam forming

Of particular importance for the competition between solid state devices and tubes is the solution given to the problem of the transmitting antenna.

Four primary transmit antenna options can be considered, as follows:

1. Single Classical Reflector Design

Potentially, the simplest beam forming configuration would utilize a single large primary reflector coupled with an offset secondary reflector placed a few meters away. One or more klystron or gyrotron generators would be positionned so that the microwaves impinge upon the secondary reflector. There are a number of ways that such an arrangement could be engineered. For example, the primary reflector could be placed on a coarse pointing mechanism, while the secondary reflector would be fully moveable to allow the beam to precisely track the user spacecraft. Such an arrangement would probably best be suited by a Cassegrain type configuration.

2. Multiple Classical Reflector Design

This concept is similar to the preceeding one, except that it uses several rigid reflectors working in an array - achieving essentially the same function as the single reflector design. Each section or module of the array, which would consist of one reflector and one or more sources (a secondary reflector could probably be eliminated), could be placed on individually moving pointing mechanisms for beam pointing purposes. This differs from the single design which would require one or more moving secondary reflectors. The principle advantage of this approach is that it breaks the system down into managable components and is easier to test. One other advantage is that it allows the possibility for upgrading through the addition of more modules.

3. Common Source Phased Array Design

This concept supplies microwaves from a common source, of one or more generators, to a phased array type antenna system consisting of several thousands of dipole elements. The microwave energy is supplied individually to each array elements via a power divider network, that is needed to apportion the energy, and the appropriate phase shifters and distribution waveguides.

4. Individual Source Phased Array Designs

A high technology option that could provide an elegant solution to many of the problems encountered with the previous options, is the use of individual solid state power amplifiers (SSPAs) as the source and antenna of the microwaves. Such a system could consist of many tens of thousands of such SSPAs, each capable of emitting between 0.5 - 1 W of power.

Such a design would not require a separate microwave source or a precision pointing mechanism. In addition, the phase shifters, which are a significant technological problem in the previous option, would be placed before the SSPAs. However, because SSPAs are notoriously inefficient (approximately 30-40% of the input power), considerably larger electrical power sources would be needed, compared with klystron or gyrotron based systems, for example.

Conclusion regarding beam forming

All four concepts have their own merits. For the long-term however, the concept of phase-array antennas using paralleled tubes of solid-state devices seems to be in preferable in principle, for the following reasons:

- the choice of sources is greater if one can have several in parallel rather than one single source;
- use of several paralleled sources provide graceful degradation in case of the failure of one or several elements (instead of a single point failure as in the case of a single source);
- the efficiency and operability of phase array antennae is very good. In particular use of a phase array enables to steer the beam in real time and direct it to the target much more efficiently than conventional antennas.

1.1.5. Reception

Reconversion of microwave power at the receiver by means of solar cells has been envisaged in the past. At present half-wave dipoles constitute a well-tested technology. Such dipoles are inexpensive and efficient.
Typically, the efficiency of the combined collection/rectification process investigated for the satellite power systems is over 90%. (The efficiency is even higher if the demand is for a.c. rather than d.c. current).

Rectifying antennas (rectennas) with 92% efficiency able to convert 1 kW per kg of mass were reported as early as a decade ago, and lifetime of their components is expected to exceed that of the spacecraft... This technology is available in Europe.

1.1.6. Summary of Microwave transmissions

In summary, microwave transmission of power from a spacecraft is sufficiently advanced to permit experiments and pre-operational use in the next 10 years.

A typical transmission balance for space-to-space would be as follows:

Conversion efficiency: 60% (klystrons)
Transmission: 90%
Re-conversions efficiency (dipoles): 90%

Global efficiency: 0.486

However, at a wavelength of 1 cm, a transmission efficiency of 90% could be obtained, with a transmitting antenna of 10 m diameter and a receiving rectenna of 4 m diameter, at a distance equal or inferior to 1.3 km only.
In practice, even with submillimeter waves, the feasible distances will be limited to a few tens of kilometers only.

The main problems to be solved are engineering problems:

- adaptation of existing tubes to space needs by:
  - optimizing masses and dimensions (n.b. dimensions of today's klystrons for continous use in fusion research at frequencies of a few GHz is of the order of two meters)
  - modifying the electrical design (ground based klystrons use very high voltages that should be avoided in space conditions)
  - extending the lifetime of critical components such as sources
  - providing space-qualified reliability.

(It has been estimated that such adaptation would require wome 5 to 7 years work)

1.2. Laser transmission

1.2.1. Principles

The benefit of short wavelengths in reducing power beam diffraction has been noted above. Laser beam dispersion in space is virtually negligible, allowing the use of much smaller transmitter and receiver antennas than microwaves of submillimeter wave systems even at long distances.

Laser power transmission however faces difficulties in both converting primary power into laser power and reconversion of power back into useful electricity. In addition, pointing problems pose a severe technological problem especially when the level of power forces to have cooled optics, when the distances are great and when the transmission is between two objects in motion or when the atmosphere is to be crossed.

1.2.2. Conversion of energy into laser beam

1.2.2.1. Types of lasers to be taken into consideration

Basically, lasers can be grouped into three families:

- the Gas/Chemical lasers,
- the Free Electron lasers,
- the solid state lasers family, in which one can distinguish:
  - the solar pumped solid state lasers,
  - the electrically pumped solid state lasers.

GAS LASERS

Gas lasers, such as excimers, copper vapor etc., have low efficiencies and, moreover are difficult to handle in space, being very large instruments, using large quantities of chemical products.
Since, in addition present large power gas lasers have been usually designed to provide short duration bursts, this family of laser is not the most likely candidate for transmitting electricity from space.

FREE ELECTRON LASERS

FELs, at present under intensive development in the US, USSR and Europe, permit to qenerate high power beams at hich frequencies. In the USA, they are taken into consideration as ground-based beam weapons. They are effective at small millimeter wave frequencies, and have attained pulsed power level over 1 GWe.

Although the technology is still in its first steps, Free electron lasers are very promising in the long term: large efficiencies could be attained (figures up to 40% and even 70% has been quoted).

In addition, FELs offer the possibility of choosing the emission wavelength to match the peak of sensitivity of the receiver or a band of eye safety (e.g. 1.54 micrometer). The amplifying medium is essentially the vacuum, and, consequently, it is not perturbed by power effects.

Present FEL's are cumbersome and heavy (several tons). However, at the long term, they could be adapted to space uses and appear as an optimal technology for long distance, continuous wave energy transmission from space platforms.

Two candidates are particularly attractive:

- induction FEL,
- radio frequency (RF) FEL.

SOLID STATE LASERS

Semiconductor lasers are commonly used today.
They have a good conversion efficiency (30 to 40% in laboratory conditions).
They are operational for very long transmission ranges at low power (for example in telecommunications - as, for example, in the SILEX programme of ESA). However the unit power of such lasers is small, and it remains difficult to constitute phased networks permitting to have a good quality beam. In other terms, the problem of large powers is yet to be solved.

Another problem is the emission wavelength.
The ideal wavelength would be situated in the 0.6 - 0.8 micron region, permitting to use silicon cells at reception. However for the near future, available solid state lasers capable to be operated in space seem to be those using the YAG:Nd technology, and emitting at a wavelength of 1.06 micron, which leads to poor absorption efficiencies.

Solid state lasers can be either optically or electrically pumped.

OPTICALLY PUMPED LASERS

Optically pumped lasers can be

- laser slabs, pumped by a flash light, a technology that is practically available at the present time, but that has its limitations.

- solar pumped lasers, which convert directly into a laser beam the solar energy, absorbed directly by an amplified medium.

Present solar pumped lasers are not very efficient, mainly because the amplified medium has often narrow absorption bands, or absorption bands not well centered inside the solar spectrum. There are hopes however, that with new solid state materials (e.g. Ti:Al2O3), which possess wide, well centered absorption bands, much higher efficiencies could be obtained. If these hopes are verified, solar pumped lasers, which avoid the conversion of solar energy into electricity, could constitute the preferred solution for power generation and transmission in space.

ELECTRICALLY PUMPED LASER ARRAYS

Electrically pumped solid state lasers are the types preferred at the present time for space applications, because of their compactness and reliability. The main types are:

Semiconductor laser arrays

i.e. large arrays of laser diodes, phase-locked to obtain a coherent and intense laser emission.

Numerous companies are involved in these developments.
The main advantages of semi-conductor lasers are the electrical efficiency (about 30% for commercial devices and more than 40% for laboratory devices), the reliability and the potentially low cost. However the possibility of obtaining high power arrays capable of levels of 100 Wt to 1 kW is not clear at this time.

Diode pumped solid state lasers (DPSL)

DPSL have proved to be reliable and to give a very good beam quality for low powers.

Nearly diffraction-limited beams with more than 12 W of cw power have been obtained, and wall-plug efficiency up to 15.8% has been attained (using Nd:YVO4 in the longitudinal pumping arrangement with 0.75 watt of ouput power).

However, when scaling at upper power levels, longitudinal scheme is more difficult to achieve since energy must be distributed along the amplifying volume.

In most cases, transverse pumping is adopted when higher power levels are desired. In that case, since the pumping volume and the cavity mode are not well matched, the wall plug efficiency is always lower: 5 to 8% with Nd:YAG.
In Europe, the 1 W level is currently obtained and the 10 W level is planned for 1991 with a Nd:YAG diode pumped solid state laser.

A typical efficiency budget with diode pumped Nd Laser would be:

Laser efficiency: 30%
Diode efficiency: 30 - 50%
Overall efficiency: 9 - 15% overall.

1.2.2.2. Most promising technologies for power transmission and crucial points.

In the very short term, solid lasers pumped by diode lasers seem to be the only means capable of generating a beam close to the diffraction limit, and that for medium size power levels (of the order of a kW). The efficiency is however rather weak.

If the technology of phase-locking diode laser networks is successful in the near future, and if significant power levels can be attained in the fundamental mode, this type of laser ought to supplant the preceeding type, with a global efficiency 6 times greater or more, with less complexity of the system.

Solar pumped lasers have been the object of numerous studies in the USA (NASA in particular). If the development of new amplifying media proves successful, a relatively high global efficiency (probably of the order of 10%) and a high power could be attained. Unfortunately, very few development actions aimed at space applications are underway.

Since the first emission in 1976 by J. Madey, free electron lasers (FEL) have progressed and could be good candidates for energy transmission essentially from earth to satellite and, later on, for orbital stations. Main advantages expected from FEL are:

- tunability of the wavelength (RF.FEL),
- high quality of the laser beam,
- high efficiency.

However significant progress remains to be made before space-based FELs can be envisaged.

1.2.3. Beam forming and pointing accuracy

1.2.3.1. Problem definition and requirements

For a high efficiency system, the transmitted power has to be absorbed completely by the receiver, i.e.:

- the beam divergence has to be reduced to a maximum extent
- a high pointing and target tracking accuracy has to be achieved (and low line of sight (LOS) jitter).

In addition, one must also take into account the problem of target acquisition and, in the case where the atmosphere is to be crossed, absorption and turbulence effects.

1.2.3.2. Diffraction

The advantage of lasers from the point of view of diffraction has been mentioned above.

Realisable sources are characterized in particular by a quality factor, which is the ratio between the actual beam diameter versus the diffraction limited diameter.
Obviously, the possibility of have quality factors as close to 1 as possible is a prerequisite for long distance transmission.

1.2.3.3. Environmental and safety aspects

Three types of effects have to be taken into account for space power lasers:

- security for the vision of human beings, in space as well as on the Earth;

- impact on the atmosphere and on the terrestrial environment, in the case of high power transmission;

- safety for objects crossing the laser beams.

Ocular security can be greatly enhanced if the laser beam wavelength is above 1.4 micrometers.

Impact on the atmosphere is reduced if the absorption of the beam is weak: there are a large number of suitable windows in the visible and infrared spectrum. A good compromise could be a narrow band about 1.54 micrometer However there exists at present no laser source available at this wavelength (but availability of FELs could modify the situation) and performing receivers are also lacking.

Safety of objects flying accross laser beams can be ensured by controlling the beam intensity, by having available exact data on the trajectory of such objects, by having recourse to detection systems with rapid obturation systems, capable of shutting down the emission in case of need.
This last security system is also to be used if an anomaly is detected in the energy level received by a target.

1.2.3.4. Beam pointing

The pointing accuracy needed, for reasons of efficiency and of safety, in the case of a transmission from space to the earth surface would be of the order of 0.05" (i.e. 10% of the divergence angle).

This accuracy is one order of magnitude less severe than what is obtained in the most advanced astronomy satellites. Nevertheless this is a difficult requirement.

In the case of a space-to-space transmission, the pointing precision needed is usually smaller than in the case of space to earth transmission, even at distances of several thousand kilometers, but this varies with the distance and with the dimensions of the transmission optics and of the receiver.

A pointing system usually includes an assembly of two main subsystems.

- a coarse pointing assembly which has a wide angular range (180 degrees) and low dynamic performance. This system generally supports the telescope and the fine pointing assembly. A beam director should be mechanically isolated from the support dedicated to this function.
- a fine pointing system which has low clearance (approximately 50 mrad) and high dynamic performance. It may include the secondary mirror of the telescope as a tilt mirror. The static and dynamic performances of this fine pointing and focusing system greatly depend on the laserbeam's wavelength and diffraction on the telescope's magnification.

Coarse alignment of POWERSAT can be very precise: the Instrument Pointing System (IPS) developed by Dornier for use in the Shuttle bay, has a nominal accuracy of 1 arc sec. However fine pointing remains needed, and is assured by

a) isolating of the transmitting systems from the environment of the satellite, i.e. from the frequencies that can be induced in the platform by actuators such as reaction wheels, thrusters etc.

b) using one or more afocal magnifying systems to adjust the diameter of the laser beam to that of the emitter optics. The more simple of them is made of two mirrors (Cassegrain mounting).

The pointing of the large primary mirror is made by moving all the satellite. The small secondary mirror has many degrees of freedom in order to assume pointing and focussing. If a free aberration system is needed, it is possible to use a deformable mirror to compensate aberrations and coherent optical adaptive technique is used to focus perfectly the beam on the target.

1.2.4. Reception cf laser beam and reconversion into electricity

Several possible receivers can be envisaged for laser beam reception and conversion into electricity, based on the photovoltaic effect, or on the conversion of the impingent beam into a heat flux, which can be subsequently transformed into electricity.

Much is expected in particular in the USA of the developments of wave energy exchangers , used with Brayton cycle gas turbine conversion systems. But, although overall reconversion efficiency is, in theory, of the order of 40-50%, the technique is still at laboratory stage and remains to be demonstrated, for terrestrial as well as for space uses.

Of more immediate interest is the use of photovoltaic cells.

New types of solar cells being developed to obtain very high efficiencies.
It is unfortunate however that present research has focussed on wavelengths less than 1 micron. This corresponds to the good part of the absorption spectrum of the cells. The maximum efficiency of a conventional silicon cell for monochromatic light is between 700 and 900 nm. This is also valid for GaAs cells.

This results, as was already mentioned above, that the absorption of a beam with a wavelength of 1.06 micron (usual with YAG:nd lasers) in unacceptable losses.

A comparison between the absorption efficiency at 0.8 and 1.06 micron in the case of special solar cells optimised for the reception of monochromatic light (polycrystalline cells) gave the following figures (at the beginning of life): sensitivity at 1.06 micron: 0.1875; sensitivity at O.8 micron: 0.52.

It is hoped that tuning the cells to higher wavelengths will be possible in the future, but much remains to be done in this field.

1.2.5. Summary of laser transmission

From what preceedes it can be concluded that laser transmission of energy

a) is feasible in the relatively short term, since all equipments for a laser power beam transmission chain in space practically exist, i.e. laser sources (solid state), optics and pointing systems (already used for astronomy and scientific satellites) and receivers (solar cells).

However, transmission efficiencies are rather small, as indicated by the following balance.

Laser efficiency
(semiconductor laser, pumped by laser diodes): 5-10 %
Transmission: 90 %
Re-conversion efficiency (solar cells): 30 %

Global efficiency: 1.35 - 2.7 %

b) can become significantly more efficient in the long term future, with the advent of new laser sources (FELs in particular, and perhaps solar pumped solid state lasers) and with more efficient receivers.

Possible figures could be, with FELs

Laser efficiency (FEL): 40%
Transmission: 90%
Re-conversion efficiency (tuned solar cells): 50%

Global efficiency: 18%

In other terms laser transmission could attain efficiency figures, for long distance transmission, not so lower than those expected, at much shorter distances, from submillimeter microwaves, but present figures are still very low.

The future of this technology depends upon the success that can be obtained in the development of new types of laser.

1.3. Mechanical connections and cable transmission (tethers)

The "plug-in" solution could be valid, for example, in the case of recoverable platforms. It could make sense, instead of providing such platforms with attached electrical generators that have to be brought back after each mission, to launch a long duration powersat that would remain in orbit and to which the platform would connect each time it is placed on orbit. This solution poses engineering problems, but no real high technology challenge.

The "tether" solution can be valid for distances much greater than what is generally expected: probably up to 100 km.

Cable transmission of electrical power can be envisaged with light cables, composed e.g. of Kevlar 49, which combines high tensile strength with low weight, a conductive coating and protection against atomic oxygen erosion.

Preliminary investigations have been performed with total transmitted power up to 20 kWatts over lengths of some 10 km. Main problems are connected with the environmental conditions. Physical damages to long tethers are one of the main hazards.

In addition, a tether between two space objects establishes a solidarity between these two objects that has consequences on the dynamic of the system, but also on its electrical behaviour. These effects are not well known, and only a continuous programme of investigations in space can permit to assess them.

A first experiment which will concentrate on the dynamic effects,is programmed in cooperation between the USA and Italy in 1992.

It is thus difficult, at the present stage, to assess the potential long tethers for power transmission. However this technology could prove useful in the long term, and even lead to innovations in fields such as electrical power generatiuon and energy storage in space.

1.4. Conclusion on Transmission Techniques

The examination of the three possible transmission technologies can be concluded as follows:

- Mechanical connection

"plug-in" connections can be envisaged immediately.
Cable connections can probably be envisaged in the long term for distances probably up to 100 km, but this technology is still to be proved in space.

- Microwave and submillimeter waves transmissions

The technology is potentially ready, at least at power levels of a few hundred kilowatts and at frequencies of the order of 20 - 30 Gigaherz.
Efficiency is good. However only relatively short ranges can be envisaged (a few tens of km maximum).

- Laser transmissions

Good transmission efficiencies can be envisaged at large power levels and for long distances if the developments that are underway in various countries are successful.

2. Uses of the remote space power concept

2.1. Space-based production of electricity for terrestrial needs

The SPS reference system was designed to supply 5 GW of electrical power to a 10 by 13 km elliptical rectenna on Earth utilizing a 1 km diameter antenna. The preliminary work established that there were no fundamental technological obstacles to be overcome. However, the sheer magnitude of the project and the unprecedented front-end cost served to curtail further research and development in the area.

New technological developments, are however likely to contribute towards lowering the costs and alleviate the environmental problems.

Such improvements concern energy generation, transmission and storage, using lunar materials for manufacturing solar cells or structural elements etc.

But, obviously, the goal of exploiting space solar power stations can be reached only if an ambitious long term technological development programme is adopted, bearing in mind that economic and environmental considerations are to be integrated in developing the technological systems and components.

This situation calls for a progressive approach.

An ideal approach is one that allows an early start of basic research and technology and provides the capability to prove the validity of the concept before large investments have to be made.

A natural progression would be to experiment first with space-to-space transmission in Low Earth Orbit before attacking the problems linked with the transmission across the atmosphere from space to the Earth's surface.

Coherence requires that:

a. In this experimental programme, maximum use should be made of space programmes already decided, such as, in particular, the Freedom programme of the USA and the European Space Infrastructure programme. As far as possible, these early experiments ought to be integrated with such programmes, and appear, as users of existing hardware rather than reasons to engage into new developments.

b. This experimental programme should also take into account the possibility that remote power technology could find an exploitable market as early as possible, and without waiting for the full deployment of the SPS system.

Recent studies have shown that such a market, as a matter of fact, existed. This is the establishment and exploitation, in space, of relatively modest power stations, capable of beaming electricity to other satellites, what we have called "POWERSATs".

2.2. Space to space energy: the POWERSAT concept

Any spacecraft, whatever its type, mission or size has a vital dependence on its power supply. The on-board subsystems and the payload cannot function without an input from the electrical power supply. It is frequently found in the design phases that a mission may suffer some limitations if sufficient power is not forthcoming. Experience tells us that the demand is always for more power, never less.

The most widely used power source for spacecraft is the photovoltaic solar array. The simplest form of solar array consists of panels attached to the body of the satellite, which must be deployed when the spacecraft is positioned in its operational orbit. This means the provision of a complicated mechanism which can unfold or unroll a flexible Kapton blanket on which some tens of thousands of cells, together with their interconnections, are mounted.

The solar arrays are large flexible appendages which have dynamic characteristics arising from disturbances which can have strong adverse effects on the design of the satellite on-board attitude control subsystem. Also, because the arrays are large they can also have a limiting effect on the fields of view of antennas and sensors.

These arrays, to sum up, add a considerable burden to the spacecraft.

Bearing in mind that the only purpose of a satellite is to carry a payload in orbit to perform a range of tasks, then consideration must be given to ways of improving the mass ratio of the payload to the spacecraft, and to simplify the design.

This result could be achieved by taking the solar array off of the operational spacecraft and placed onto a much simpler spacecraft which is flying in line-of-sight of the operational spacecraft, and is provided with some means of transmitting the power to that spacecraft, i.e. by using a POWERSAT.

Market evaluations regarding the number of spacecraft likely to have recourse to remote power have been performed in the course of 1989, in particular by EUROSPACE. These evaluations, can be summarized as follows.

The largest proportion of the electrical power is expected to be consumed on the geostationary and highly eccentric orbits, essentially by communication satellites, (although some Earth observation and scientific satellites will be situated there also), the consumption on low altitude, low inclination orbits promises to be important also, the consumption expected on other orbits is lower and large power needs for lunar and planetary bases will probably be felt after 2010 only..

Table 2. Distribution of Civilian Spacecraft per Orbit

(Period 1995-2010)

Geostationary: and highly eccentrical	1 690 to 8 100kW
Low altitude, low inclination (space station type)	720 to 1 110kW
Polar orbit	60 to 200kW
Others (planetary probes etc.)	30 to100kW
Space power for lunar and other planetary bases?	
Total	2 500 to 9 510kW

The most favourable location for a first application of the POWERSAT concept is without any doubt the low altitude, low inclination orbit, and, more precisely, the orbit of the international space station "FREEDOM".

A list of the main projects of interest for Europe under preparation for this orbit is as follows.

- **The space station itself**

This station is to be placed on a 28.5 degrees inclination orbit, at an initial altitude of some 410 km. The project has been submitted to several re-definitions, and, in particular, its power has been reduced to a level that will probably make an augmentation necessary in future years.

- **The US and International space Infrastructure**

The US space station is to be complemented by co-orbiting platforms and laboratories developed in the USA, Europe and Japan, such as

- US and European co-orbiting platforms (the German SPAS and its successor, the European Eureca etc.);
- Visitable privately owned stations (the US Industrial Space Facility, e.g.);
- An autonomous visitable Japanese module,
- The European Columbus Free Flying Laboratory (CFFL), a pressurized module (previously called MTFF - for "Man-Tended Free Flyer").

Also account should be taken, probably in the more distant future, of the possibility to use remote electricity for powering electrically propelled interorbital vehicles (Use of POWERSATs for such vehicles would make sense,due, in particular, to the unsuitability of attached solar cell arrays, solar arrays having a high ratio of mass to power output and being unable to get through the Van Allen Belts without shielding).

Thus the number of infrastructure elements and platforms potentially interested in the services of a remote electrical power plant on orbits close to that of the space station can be considerable in the not too distance future.

The main argument in favour of the remote power plant concept is that its cost, at least after the development period, ought to be lower than that of individual power systems.

Four aspects dominate the cost situation in the case of individual solar power systems:

- the unit cost of individual solar power plants, which is due to the fact that each spacecraft is often a particular case, and that as a consequence, the benefit of economies of scale or learning curve remains very small;

- the high impact, in particular in the case of large systems, on the global system cost; the risk of mission failure;

- the high cost of changes during the development or, a fortiori, during the mission.

- the high cost of the electrical KWh in the case of short missions.

Power beaming could be applied

- either as a total replacement for existing on-board systems,
- or as an augmentation to the existing on-board power supply,
- or as a back-up to existing on-board power supply.

Average cost per Kilowatt-hour in space vary considerably from mission to mission but figures superior to 4 000 US $/Kw-hr have been quoted in the case of short duration missions.

Standardization of the power generation and management functions of a medium-sized POWERSAT (10 to 20 kW continuous electrical power) launched on a low earth orbit would probably permit to lower the cost of electrical power on-board the POWERSAT to less than 600 US $/kw-hr. Cost and losses of efficiencies in the transmission system would bring the cost of the electrical power received by the serviced spacecraft to some 3,000 $/kw-hr (less if the POWERSAT is used for several spacecraft), with technologies envisageable for the end of this century, but this level could be attractive for several categories of users.

2.3. Synergy between SPS development and POWERSAT programs

There is a clear synergy between the SPS and Powersat programmes.

The time schedule that can be envisaged for the development of a SPS programme, if this programme is viewed from Europe, is that given on Fig. 3.

Basically, the activites start with system studies and an enabling technology programme, bearing in particular on the development of energy transmission technologies.

Small scale transmission experiments would then be organized to test the technologies developed, based, in particular on the use of such elements of the European space infrastructure as Eureca, the SPAS recoverable platform, the Columbus Free Flying Module etc.

The next phase would be the development and operation of a large demonstration plant, of some 1 MW power. This plant could begin to be assembled on the Low Earth Orbit in the early 2000's using, for example, the Hermes spaceplane. The purpose would be the verification of the performances of the essential system. In principle, the preference would be given to laser transmission. (The hypothesis was made of a step function increase in laser conversion efficiency around year 2012).

Fig. 3

Envisageable schedule for SPS development

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: POWERSATS             :  :  :  :  :  :  :  :  :  :  :  :  :  :  :  :  :  :  :  :
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The interesting point is that the experimentations in space of transmissions can take the form of the development of a POWERSAT development programme. A possible date forbeginning preliminary powersat operations could be year 2002. The POWERSAT concept appearing, in fact, as the enabler of quite a family of possible applications.

It can be noted that, even if the decision was ultimately taken not to build a SPS system, the hardware developed for the 1 MW development to be used for operational space to space transmission.
In other terms, whatever the ultimate application of the remote power concept is to be, in-orbit experiments by means of platforms that can be used as POWERSATS are the growth path.

4. Planning of early experiments with POWERSATS in LEO

System and engineering aspects essential in the POWERSAT perspective (in addition to the transmission aspects reviewed above) are as follows.

4.1. System aspects

The most probable first application of the remote power concept is the use of microwave POWERSATS in LEO.

Due to the short possible distances, it will be necessary to maintain the POWERSAT and the user spacecraft(s) on the same orbit - otherwise the distance would be subject to large variations, making the transmission difficult (and even impossible when the Earth is in the line of sight).

In addition, due to the different factors perturbing the orbits of the POWERSAT and that of the user spacecraft(s) corrective measures will have to be taken to keep distances and attitudes under control.

The corrective measures will imply compensation for solar pressure effect, air drag, etc., which has consequences on the Attitude and Orbit Control System (AOCS). The logic of using POWERSATS would imply that most of the burden of these corrective measure be borne by the POWERSAT itself.

4.2. Engineering aspects - Photovoltaic generation of electricity

Photovoltaic systems clearly appear as the preferable solution for the foreseeable future. The technology is available and progress in the field of solar cells permits to hope that much better conversion efficiencies than today's can be achieved in a few years time.

Key element for the power conversion is the solar cell. Evaluation criteria are efficiency, mass, and cost.

Baseline for present space solar arrays is be the high efficiency HEC-BSFR cell, prepared from 4"/5" Si-wafer. This cell type has an average efficiency of 14,5% under standard conditions 25° C, 1,353 w/m2, AM0. The thickness of the cell is approx. 180-200 microns, thin cells (70 microns) are available in pilot line maturity. This cell type has an optical reflector on the rear side to reduce the operation temperature in orbit.

For special application in the low earth orbit a bifacial cell/array technology has been developed. The direct sun light is reflected by the earth's atmosphere and surface (approx. 0,3 Solar Constant average). A bifacial solar array with active surfaces on the front and rear side can generate electrical current from both flux components resulting in a higher specific electrical conversion efficiency.

Baseline for future array is given in Table 4.

Table 4

Solar Cell Types for POWERSAT

	Efficiency	Target
High Eta Si-Cell	16-17%	1993
Advanced Bifacial Cell	> 20%	1995
GaAs/Si	18-20%	1995
Multijunction/Concentrator	- 30%>	2000

An improved silicon solar cell is now under development, the HIGH ETA cell. This solar cell type has been derived from the terrestrial approach, where an efficiency of > 20% has been achieved with passivated surface conditions. This new space solar cell type will be qualified within the next two years and is proposed as baseline cell for the COLUMBUS solar array.

GaAs-solar cells are an attractive alternative to silicon cells since the beginning of the photovoltaic technology. The efficiency of present GaAs solar cells is 18% verified in pilot line/production lines in the U.S. and Japan. The GaAs technology promises for multijunction cells a conversion efficiency of 20-30%. It thus is the key for a new generation of high efficiency cells.

Finally, the baseline for the POWERSAT experiment should probably be a Silicon or GaAs/Si cell with a conversion efficiency of 18-20%. For long term application multijunction cells are attractive candidates.

As concerns the solar array structure, flexible as well as rigid systems are potential candidates.

The rigid type is of advantage for solar arrays in the power range of several kW. In that case no additional deployment mast is necessary for the solar array. Most of the communication satellites in the geostationary orbit are examples of rigid solar arrays.

Typical examples of of flexible solar array are the foldable solar arrays used, e.g. for SPOT, CTS or OLYMPUS, and the roll-out type, used for the Space Telescope.

The flexible foldable solar array seems to be the preferable candidate for the power range of 10-100kW. Designs for a 40-60kW solar array have already been analyzed in detail in Europe and could be used for POWERSAT platforms in the 80kW range.

A voltage level > 120 V is required to reduce ohmic losses in the wiring and harness. This high voltage level has been identified as critical design area for plasma interactions. A vehicle moving through the earth ionosphere encounters fluxes of charged particles which generate a plasma wake, resulting in various disturbing effects, including power loss drains and arcing damages. Since simulated conditions are not fully representative for all parameters for LEO orbit conditions, in-orbit experiments would be necessary.

4.3. Summary of recommendations regarding experiments and actions

The actions and experimentations to be envisaged in the relatively near and medium-term for POWERSAT development can, be summarized as follows.

a. Energy generation

a1. Photovoltaic systems

- Improvement (on the ground) of work on large arrays
- Continuous development in all technological fields
- Technological experiments in space
- Short duration (10-14 days) experiment in LEO for plasma interaction with high voltage panel (could be done soon with small satellite in piggy back)
- Long duration (2 years) test of new solar cells modules (probably high ETA Si cells and bifacial cells). Could be done with a small technology satellite.
- Demonstration platforms and operational platforms recommended for POWERSAT concept:
  - first platform: 80kW peak power that could be developed at the end of the century, e.g. for power augmentation of Columbus autonomous module. Received power on-board Columbus could be 20kW peak, and 12kW average.
  - second concept could be a small power platform in GEO for identifying problems areas towards the SPS approach.

a2. Other systems

Continuous development sdhould be recommended, ion particular in the field of thermodynamic systems.

b. Transmissions

A reference programme for preparation of pre-operational POWERSAT on low earth orbit would comprise:

b1. for Microwaves transmissions:

- development work on ground (adaptation of existing sources to space conditions);
- low power experiments of space to space transmission could be done, using space infrastructure, towards the end of the century;
- first (pre) operational POWERSAT can be envisaged at the beginning of next century.

b2. for Laser transmissions:

- Continuous development on ground to be monitored, in particular high power sources with potential high conversion efficiency, pointing systems and receivers.
- Encouragement to the development (on the ground) of certain elements necessary for laser power transmission from space or in space
- first demonstration possible end 1994
- first European laser transmissions experiments in space to be performed, preferably with existing vehicles and platforms (beginning at the end of the century)
- first operational uses for space-to-space transmission around year 2010.

c. Engineering

Continuous monitoring is to be recommended of the progresses, in particular concerning:

- storage (NiH_2 batteries etc.)
- stabilisation
- electric propulsion
- robotics
- heat rejection, etc.

4.4. Proposed time-schedule for a POWERSAT development

The time-schedule of the proposed experiments is given in Figure 5.
This figure assumes that operational POWERSAT operations in low orbit could become possible by year 2000 with the microwave technology, and that POWERSAT operations could become economically feasible with laser technology by year 2010.

5. Conclusion

The SPS concept has been worked out with the view to supplying large amounts of electrical energy to terrestrial networks at a cost comparable or lower to today's electricity on the earth.

It was seen that a rational development schedule of a SPS programme implied the performance of transmission experiments in orbit. It was seen also that the availability, on low orbit in particular, of platforms of this type could permit to alleviate the difficulties encountered at present by various classes of spacecraft with their classical, attached power plants. These platforms could be used as POWERSATS.

This would permit to exploit a small but potentially interesting market, where the cost of electricity is much higher than on the earth.

Microwave POWERSATS installed on the orbit of the Freedom Space Station appear as the first possible application of the remote power concept.

For the long term future, the factor that dominates the situation is the possibility to significantly improve the efficiency of laser systems.

For this reason

a) development work and experiments on microwave transmission concepts should be initiated in the very near future.

b) progress in laser source developments permitting continuous energy transfer at high-power level should be encouraged by the European Space authorities;

c) no time should be lost to work on the technical problems of acquisition and pointing of laser beams, which are essential to ensure the possibility and safety of energy transfer.

Table 5
Schedule of experiments and operations in the global context of remote transmission of energy

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A7.3 Broad-based space solar power advocacy

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ABSTRACT

We believe that the proper goals of today's space program are clean energy production and biospheric remediation. Accordingly, the traditional space focus on solar system exploration with technology spinoffs makes the program appear irrelevant to the public whose taxes fund the effort. A shift in space goals toward environmental technologies like space solar power (SSP) and space recycling systems (SRS) with exploration as the spinoff would, in our opinion, revive the firm universal support for space development that was characteristic of the Apollo era. We describe public relations and public education strategies that we have begun which show promise in changing the direction of space program goals.

ABSTRAIT

Nous croyons que les objectifs mêmes du programme spatial actuel sont la production d'énergie propre et le rétablissement de la biosphère. En consequence, la concentration spatiale traditionnelle sur l'exploration du système solaire avec des dérivés technologiques, fait apparaître le programme hors de propos au public dont les impôts financent l'effort. Un changement dans les objectifs spatiaux vers des technologies ayant trait a l'environnement, telles que l'énergie solaire spatiale (SSP) et les systèmes de recyclage spatiaux (SRS), avec l'exploration en tant que dérivé, pourraient, a notre avis, renouveler un support universel ferme du développement spatial qui était caractéristique de l'epoque d'Apollo. Nous decrivons les relations publiques et les stratégies d'éducation publique que nous avons commencées, lesquelles sembles pleines de promesses en ce qui concerne le changement de l'orientation des objectifs du programme spatial.

1. Introduction

It can be argued that the successes of the free enterprise economies may be ascribed to three factors: 1) the principals of democracy that strive to provide a level playing field for all participants, 2) entrepreneurship that encourages innovation in both products and industrial operations, and 3) advertising or public relations because, no matter how great the innovation, if nobody ever hears of it, it might as well not have occurred.

2. Public Relations Problems in the Space Program

It appears to us that current space programs are seriously deficient in the third factor of public relations. We say that because it has been our observation that, at least in the United States, the average citizen, whose taxes fund the major space projects, thinks that the space program is nice but irrelevant. That is the case despite the fact that space technologies offer the greatest potential for complete solutions to the critical problems of energy dependency, environmental degradation, and industrial renewal. Concepts like space based solar power systems (SSP) are the only technologies that could conceivably relieve the biosphere of the debilitating impact of inefficient and/or polluting industrial energy production on the surface of the Earth because they can establish utilities in high orbit or on the moon. And space recycling systems (SRS), under development for closed ecological life support as well as lunar base and orbital industrial processes, have direct application to the growing environmental demands on terrestrial industry.

However, almost nobody knows that there are space solutions to the energy and environmental crises. In our opinion, that is, at least in

part, the consequence of a traditional emphasis in space program goals on exploration instead of technological applications. Technology is treated as a mere spinoff. Accordingly, accounts of the enormous technological promise of space tend to be relegated to the aerospace media which the public rarely sees, while the headlines of the mass media feature projects like Mars missions and space station which have no priority with the public.

It is our opinion that if people knew about options for space environmental technologies like SSP and SRS, and if they believed they were viable options for resolving the energy and biospheric crises, there would be substantial grass roots support for space industrialization. Such space options don't have to be proven technologies in order to generate solid broad-based support, they only need to be perceived for what they are, viable candidates to provide clean renewable energy with greenhouse abatement, and resource recovery from waste and industrial effluents.

One obstacle to the widespread dissemination of information about SSP, in particular, is the curious fact that many people in the aerospace community that are familiar with concepts like the solar power satellite systems, studied by the U.S. Department of Energy in the 70s, assume that most people have heard of SSP and have dismissed the concept. The mistaken impression may arise because aerospace professionals and advocates seem to have evolved into an isolated group whose members talk only to each other, and perhaps a few key politicians. Such inbreeding in the aerospace community is fostered by the unfortunate belief, common in all the technical and scientific professions, that you can't explain technological concepts to the general public because they are scientifically illiterate. Further, aerospace professionals seem to operate under the impression that NASA, the present Administration, the U.S. Congress, and the aerospace community are the sole determinants of space program funding and goals. The public has nothing to say about the matter. And in any case, since there is no significant funding in the U.S. for SSP or SRS, we don't have to worry about explaining those technologies to a wide audience.

These attitudes miss the point that aerospace professionals and advocates are the beneficiaries of the space program, and the ignored public is the customer. The public, after all, foots the bill. In the private sector, ignoring the customer is, of course, the fastest way to go out of business. In the public sector, it takes a little longer. We believe that the reason that space funding is so vulnerable in the United States is our failure to convince the public that space technology is both relevant and critical to many of our our most pressing current problems.

Many will argue that NASA has a sophisticated Public Affairs office that has done an effective job in communicating with the public for many years. That was undoubtedly true in the Kennedy-Johnson era when all sectors of society in the United States, both public and private, were united behind the Apollo program for reasons of national security and prestige. But that was the consequence of President Kennedy's notable success in selling a race to the moon with Russia to the American people. Or rather, Kennedy had the wit to realize that, in his time, a race to the moon with Russia would sell. In our time, it is the failure of the aerospace community to latch on to a similarly compelling goal that is at the root of its public relations problem.

We believe that there is a very compelling current issue that space technology directly addresses. That is, as we have argued above, the environment. How is it then that we are missing the opportunity to capitalize on that issue? It might be objected that NASA is in fact capitalizing on it in its Mission to Planet Earth program. However, Mission to Planet Earth is strictly remote sensing and monitoring. In that mode, NASA gives the world a grandstand seat to witness the death of the biosphere as we know it. Virtually nothing is said about how the space program can fix the environment. This is dramatically illustrated in a recently released IMAX film entitled BLUE PLANET. The film shows stunningly edited footage of terrestrial geography, ecology, geology, and meteorology as seen both from space and the surface of the Earth. We witness the desertification of the Sahel, the deforestation of the Amazon, and the growing turbidity of our atmosphere. BLUE PLANET has the impact of a beautiful tragedy. Yet, despite the fact that space observation and photography are the predominant media of the film, not one word or image suggests that space technology can remedy the crisis that is depicted. Thus Mission to Planet Earth and its offspring join in the ever growing environmentalist refrain that little can be done except perhaps to stave off, for a few more years, the inevitable extinction of the familiar biosphere through tougher environmental regulations and small scale recycling projects. It is a defeatist perspective.

Can the defeatist perspective be

reversed? We believe so. The problem with the Public Affairs Office at NASA as we see it is that it is trapped, through no fault of its own, in the outmoded philosophy that NASA's goals in space must be focused on solar system exploration with technology development as a corollary. That was the appropriate focus for the Apollo era, but times have changed. Very few people still believe that political rivalry between the free world and Russia is our greatest challenge. We no longer have to demonstrate our superiority. By contrast, everybody is acutely conscious that energy dependency, and environmental pollution are critical current challenges. These new imperatives call for a shift in NASA's focus toward energy and environmental goals with solar system exploration as the corollary. We believe that high profile programs in SSP and SRS would accomplish that policy shift and renew the firm universal support that NASA enjoyed in the Apollo era. However, as a public agency, NASA is encumbered by regulatory and statutory restraints as well as bureaucratic traditions that make it hard to effect fundamental changes in policy from within the agency. That is why we believe that the impetus for change must come from political pressure outside the agency in the same way that the revolution in United States environmental policy has been spurred by public awareness and public demands.

There is yet another problem with NASA public relations that has to be addressed. That is the public expectation that NASA ought to be infallible and that all space missions and operations must be flawless in order to be accounted successes. Those unrealistic expectations have evolved out of the spectacular successes of the Apollo and planetary missions, but they have also been fostered by traditional NASA press releases that imply perennial mission perfection both before and after the fact. Accordingly, space missions tend to be reported in the press as either flawless or failures with little leeway between those extremes. One of the most lamentable examples of this is, perhaps, the Hubble Space Telescope. Hubble is a great success. It has achieved ten times the optical acuity of the best Earth based telescopes and its analytical spectroscopic capability is as good as expected. Hubble gives regular weather reports on Saturn, has sharpened pictures of the bright supernova that appeared in 1987, and is mapping in detail the composition of planet-forming gas canopies surrounding distant stars as well as the most accurate compositions of the stars ever obtained. But because Hubble has not yet achieved the hundredfold improvement in optical sharpness that was forecast by NASA, the public thinks it is a dismal failure.

The problem is not the performance of space missions, but the perception of their performance. What can be done about that? Some blame the press for focusing on problems like shuttle delays and the Hubble focus which are minor in comparison with the achievements of the programs. The shuttle is, after all, the most complex and remarkable machine in human history. It is a space ship, an Earth observation platform, a radiation monitor, an astronomical observatory, a satellite launch and repair facility, a manned biological and material science laboratory, a glider, and more. To any one with an engineering background, its performance, in light of its complexity, is awesome. But we can't blame the press for printing problems. The press thrives on conflict. What is missing in current space press relations is a clear justification for the expense and complexity of shuttle, space station, lunar base, and other major space projects. If the justifications for such projects were understood to be clean energy production and biospheric remediation, the unavoidable problems that attend all such projects would be put in proper perspective. The problems would rarely, if ever, appear to the press to outweigh the goals. Even the deaths of the Challenger crew can be accepted with equanimity if they are understood as unavoidable sacrifices in the effort to save the home and birthplace of our species.

We believe that clean energy and biospheric remediation are the proper purpose of the space program in our time. Exploration is great, but it is not a current priority. There will be plenty of time for that after we save the biosphere, but little time for anything if we don't. Further, the development of a cis-lunar infrastructure with lunar resources, that we believe is necessary to the emplacement of space solar power systems, will greatly enhance the options for future solar system exploration. Accordingly, exploration and biospheric goals are not in conflict. It is only their relative priority that has to be righted.

3. Public Relations Strategies as The Key to Space Solar Power Advocacy

To that end, we have established a nonprofit organization that we call the Solar/Lunar Council for the purpose of developing and executing strategies that make the general public aware of the powerful remedies that space technology offers to the critical energy and environmental

challenges that confront us. Our goal is to make SSP and SRS as familiar as fossil and nuclear fuels, biomass, and recycling centers, so that space options become part of the ongoing biospheric debate.

Our first goal is to raise the profile of space issues and benefits to public view. We want to make the space debate conspicuous so that as many people as possible take notice. One approach we have taken is to address environmental groups about SSP and SRS options. We have made presentations to the Audubon Society and Sierra Club groups in Houston with very positive results. Most of the talks at meetings of these organizations are downers that bewail the inevitable extinction of the biosphere. By contrast, we have offered solutions that are more than just holding actions. You could feel hope dawning in the minds of the listeners. It was the first time most of them had heard that there are any environmental remedies at all.

We propose to expand communications and form alliances with these and other environmental groups to enlist their considerable political and organizational influence in active support of space benefits. Already the March/April 1991 issue of SIERRA, the official magazine of the Sierra Club in the United States, has cited SSP as a desirable although distant energy option. We need to update them on the technology and what is needed for continuing research.

A more broad-based strategy for engaging the public is to raise a good-natured Mars vs Moon debate. We have taken the role of lunar partisans outraged at the attention Mars is getting. The tone of the tactic is entertainment and fun. But the strategy is to surface the Mars opposition, enjoin a lusty public debate, and attract coverage from the free media. So far that strategy has has been remarkably successful. We first launched it at the U.S. National Space Society Conference in San Antonio, Texas last May. Within a week, we obtained detailed coverage in six Texas newspapers in the cities of Dallas, Austin, Houston, and San Antonio as well as the national wire services. We appeared on a radio (WOAI) talk show in San Antonio, the cover of ADWEEK, the American advertising trade newspaper, and were interviewed for the major radio news station in Houston, KTRH.

In all this media attention, we have made and will continue to make a public case for the advantages of lunar industrialization which are near-term compared with a one or two shot mission to Mars. We explain that we are going to the moon to stay this time and to begin the expansion of the local space infrastructure with lunar building materials and fuels that can provide electrical utilities, industrial facilities, and resort hotels on the moon and/or in orbit. That is, in part, because the moon's low gravity makes it possible to put large quantities of lunar derived infrastructure into space with only a few percent of the energy required to launch the same mass from the Earth. We also make the point that lunar industrial operations will require development of closed ecological life support systems and the complete recycling of industrial effluents and reagents, all of which will be immediately applicable to the increasingly stringent environmental demands placed on terrestrial industries and ecologies.

Some have objected that the negative Mars campaign is divisive to the achievement of space goals. However, the tactic was recommended by the professional public relations firm of Smith/Williams in Austin, Texas as a sure-fire way of attracting the media coverage required to disseminate the positive message of SSP and SRS options that are out there. The principals of Smith/Williams have had an excellent track record in managing the media in the political campaigns of Texas Governor Ann Richards, Lieutenant Governors Bullock and Hobby, U.S. Senator Lloyd Bentsen, and Congressman Jake Pickle. And their recommendations have worked! The fact of our media success has won over 90 percent of our critics. In particular, our contacts at NASA in the Space Exploration Initiative program are very pleased. They realize that while they are not in a position to pump up the press on these issues, we are, and they are delighted we are doing it. Still, there is a tendency within the aerospace community to regard public relations tactics as slightly disreputable. But, as we have argued above, the traditional aerospace approach to the media, both within the government and the space advocacy community, is working at cross purposes to space development. We believe that a fresh approach is required, and that is why we have retained public relations professionals outside the government and aerospace sectors.

Future plans include newspaper and magazine ads, as well as radio and television commercials. A commercial for the local radio market in Houston, Texas has already been produced. It is a 60 second spot that announces the potential for establishing lunar derived space solar power systems. We have also been invited back to San Antonio to do an hour talk show on the strength of our first radio appearance

in that city in late May. The hosts of the talk show said that we made the space program intelligible to them for the first time. In addition, we are exploring the possibility of including SSP and SRS material in a nationally syndicated Saturday morning television series for children being produced by the Spacewatch Club in Houston, Texas. The goals of the Spacewatch Club closely parallel those of the Solar/Lunar Council with the focus on a children's audience. The Spacewatch series is scheduled for international distribution by the Paragon group in Canada and through Video Cosmos in the Soviet Union.

In the area of communicating technical ideas to general audiences, we have found the public to be quite educable. We describe SSP as simply an extension of the most successful commercial space enterprise, the communications satellite industry. We explain that just as communications satellites transmit information to Earth on radio waves, larger satellites in the same orbit could communicate electric power to the Earth on similar radio links that are only a fifth the intensity of sunlight. Everybody knows that communications satellites don't go out at night, so it's easy to show that power communication from the same orbit would be virtually continuous. As for the public fear of microwaves, we have found that to be a minor issue. We explain that sunlight is more harmful to your health than the microwave link proposed. Everyone is used to microwave ovens and we leave our audiences yearning for microwave replacements to fossil fuels and nuclear reactors. It is notable that the reference to SSP systems in the spring issue of SIERRA mentioned above says nothing about microwaves. We do not suggest that SSP presents no problems or that it is a sure thing, We represent it, rather, as a feasible extension of existing and mature communications technology that requires development of a lunar-sourced space infrastructure.

As we perceive it, the traditional problem that scientists and technologists have in communicating with the public is a case of telling their audience what they think it should know instead of discovering what important information the public wants to know and how to communicate that information with accessible concepts and language. For example, the public may already be surprisingly sophisticated about the Moon versus Mars issue. One of our associates recently asked a cab driver on the way to the airport how she felt about going back to the Moon versus going to Mars. Her answer was, "We ought to finish what we started". That kind of answer suggests that our task may be as much consciousness raising as education.

With regard to the technical feasibility of SSP, SRS, and lunar energy sources like helium-3, all of which are enhanced or made possible by lunar development, a large body of literature and some field data, have already been developed, particularly for the various energy options (O'Neill, 1975; Glaser, 1989; Kulcinski and Ott; 1989, Criswell and Waldron, 1990). We feel very comfortable in enjoining the technical debate that we hope to stimulate through our public relations campaign. And we are confident that when all the facts of the proposed terrestrial and space solutions to the biospheric and energy crises are openly compared, space options like SSP and SRS, and all the attendant space transportation, orbital operations, and lunar surface systems that they entail will win firm research and development funding.

4. Conclusions

We all recognize space as the new frontier, and no one can seriously challenge the remarkable technical advantages that have flowed from that endeavor nor the vision that it has inspired, particularly in our youth. We are convinced that when the public understands that space is a real avenue to energy, environmental, and economic renewal and competitiveness, they will clamor for it. Contrary to conventional wisdom, it is our opinion that both the government and private sectors are very responsive to broad-based public opinion. As a current bumper sticker puts it, "If the people lead, the leaders will follow".

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A7.4 SPS technology development strategy in the context of the space exploration initiative

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ABSTRACT

The Space Exploration Initiative (SEI) concerning the establishment of a permanent manned base on the moon, an then the exploration of the planet Mars by Astronauts, have begun to be the subject of studies in all space active countries, in view of preparing strategies for the future.

This initiative will take place before the first operational SPS will exist, for obvious reasons. But SEI implies the development of many new technologies before the target year 2019.

Many of the technologies for SEI are common with the ones needed for SPS development. In this context, a strategy for SPS preparation is proposed.

RESUME :

L'Initiative d'Exploration Spatiale (SEI) se propose d'établir une base habitée permanente sur la Lune, puis d'envoyer des astronautes explorer la planète Mars. Dans tous les pays spatialement actifs, ces idées ont commencé à être l'objet d'études en vue de préparer les stratégies du futur.

Cette initiative sera mise en place bien avant que le financement du premier SPS opérationnel soit décidé, pour des raisons évidentes. Toutefois, la SEI implique le développement de nombreuses technologies nouvelles avant l'objectif clef de 2019, et beaucoup de ces technologies sont communes au SPS et à l'Initiative. Dans ce contexte, il convient de revoir la stratégie de préparation de l'ère des SPS.

INTRODUCTION :

On july 20, 1989, US President Georges Bush issued a bold chalenge for the future of space programs : the Space Exploration Initiative (SEI).

The Initiative has two major objectives : a return to the Moon, early in the next century, to create a permanent manned lunar base, and a human mission to the planet Mars before the year 2019.

To meet this chalenge, many innovative exploration technologies must be developed, in a context of a long range, international, continuing commitment to exploration. As such, it provides the new strategic framework for civil space planning, with the necessity of a new and enduring

emphasis on space technology investment.

This is exactly what will be needed also for a large scale SPS program.

Let us look at the identified technology needs of SEI that are common with SPS.

Of particular interest are the following building blocks :

- Earth to LEO transportation
- In space transportation
- In space operations
- Information systems
- Communications

where the goals include risk reduction, reliability improvement, cost reduction, and performance enhancement.

EARTH TO LEO TRANSPORTATION :

This domain will be a very critical requirement for SEI : needs are to develop new transportation systems to LEO in order to obtain highly reliable vehicle operations and launch, with a large cost reduction and a large increase of mass launched.

This is exactly what have been said for SPS, with probably more than one order of magnitude more mass to launch per year.
A lower launch cost is very crucial for SPS future, because the economic viability of electricity from space will be mainly driven by transportation costs.
With SEI, the development cost of large transportation systems will not have to be included in the SPS program, and as SPS would use much more launches per year than SEI, the costs per kilogram of SPS in LEO would be less than the one obtained by SEI.

IN SPACE TRANSPORTATION :

The concept of transportation of men from LEO bases to the moon have to be entirely improoved as compared to the Apollo era. Again, the need to have large amounts of mass transported on a regular basis necessitates drastic improovements in cost and risk reduction. Automated and piloted vehicles will be developed during SEI, including low and high energy aerobraking techniques, space based cryogenic refueling, autonomous rendezvous and docking ... etc.

But, we know that it is about the same to go to GEO or the Moon orbit on the delta V point of view. So, SEI will develop in this field exactly what SPS will need in a later step.

Even at a detailed scale, the need to have cargo and astronauts using different kinds of transportation systems is shared also by SEI and SPS. This is why in both initiatives, rapid, cryogenic propulsion as well as slow, low cost electric spiralling are recognized interresting techniques to develop.

IN SPACE OPERATIONS :

SEI will rely on movement of equipment as well as the SPS construction and maintenance in orbit. Particularly, in both programs, a large use of in orbit assembly, manned and automated will be needed. For this reason, reusable vehicles, EVA or robotic oriented, will be used by SEI. The only difference is the larger number of these vehicles for SPS.
The need for deep space expeditions in SEI, with the new capabilities implied to insure safe and productive long term human participation : regenerative life support, radiation protection, efficient EVA, advanced man-machine interfaces ... etc, will give SPS a lot of experience on critical aspects.

INFORMATION SYSTEMS :

During the preparation phase of SEI, a large use of robotic missions will be necessary. Of particular importance are, for Mars exploration, the techniques for autonomous intelligent vehicles and scientific systems. A large array of new electronic systems will be developped at this occasion, all able to reduce dramatically the costs of SPS construction and maintenance.

COMMUNICATION SYSTEMS :

Communications in SEI are an important domain, their complexity due to the operational aspect, the large number of networks involved, and the problem of high rates of information exchange at Mars distance necessitates developments.

For SPS, a similar situation exists, during the complex contruction phase as well as the maintenance one.

Technologies needed for microwave energy transport will be probably improoved by SEI, due to the many energetic problems to solve both on the Moon and on Mars.

POWER SYSTEMS :

This domain of SEI development is recognised very critical, and many different techniques will be needed. Of particular importance are the solar generators for the moon base, because they will be the only way to maintain the life of the astronauts there. On the moon surface, the nights are very long (14 earth days) and the question of energy production and storage fondamental for regenerative life support systems.
For obvious reasons, it seems that a particular effort will be done by SEI in all aspects of the energy problem.
This will be a tremendous occasion to advance, test and improove the solar energy techniques needed for SPS

IN CONCLUSION :

The Space Exploration Initiative, quasi decided, appears to become soon a very active technology driver. But, as a large majority of the new techniques needed in SEI will be applicable to a future SPS program yet far to be decided, it appears important to study in detail all the commonalities of the developments for the two kinds of programs.
Both SEI and SPS would be improoved in credibility during this process

May we suggest also that SPS supporters become soon active supporters of SEI, and then developpers of SEI/SPS technology.

This approach would, for sure, be excellent on a mankind perspective.

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SPS 91

A7.5 Space Solar Power Program (SSPP) design project for the international space university 1992 summer session in Kitakyushu, Japan

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SUMMARY

This presentation outlines the design project to be conducted at the 1992 Summer Session of the International Space University (ISU'92) which will take place during July and August of that year in the city of Kitakyushu, Japan. The international space power community's support for this endeavor is currently begin sought.

RESUME

Cette présentation évoque quel sera le projet d'étude mis en place durant la session d'été 1992 de l'université internationale de l'espace (ISU'92) ; session qui aura lieu durant les mois de juillet et août dans la ville de Kitakyushu, au Japon. Le soutien de la communauté internationale du pouvoir de l'espace (international space power community) est aujourd'hui solicité pour ce projet.

RATIONALE

Each Summer, the International Space University selects one or more projects of an international nature as the subject of a multidisciplinary design project which includes students from such diverse fields as space engineering, policy an law, life sciences and others. The board of directors of the International Space University has approved a Space Solar Power Program as the primary project for the 1992 session.

The growing global demands for electrical power and increased international awareness of the problems of fossil fuel emissions are combining to enhance interest in space solar power as a potential solution to terrestrial power needs. Also the potential to use space to not only monitor planetary environmental conditions but to actually help effect positive change makes space solar power the ultimate "mission to planet Earth." The development of these global systems will, by definition require international accords for implementation. The interesting and unanswered question of how developing nations can participate in power from space projects might best be discussed within in an international setting.

In addition to terrestrial needs for power is the need for additional power generating and transmission capacity in space itself. Beamed power for earth orbit facilities, orbital transfer vehicles and lunar and planetary bases has been contemplated with levels in the kilowatt to megawatt range. Glaser and others have suggested that supplying these needs could provide the technological and the financial steps to large scale space solar power for the Earth.

BACKGROUND

The International Space University has conducted five design projects during its first three Summer Sessions. The inaugural ISU session, held at the Massachusetts Institute of Technology in 1988, featured the design of a lunar base to support Solar Power Satellite construction, as the first ISU design project. Subsequent projects (IAM and LPO) have also been relevant to the solar power satellite project. In addition, the concept of large scale space solar power as well as traditional uses of space power for exploration, propulsion and bases are part of the existing ISU core and advanced curricula.

Two of the ISU departments -- Space Engineering and Space Resources and Manufacturing -- will play a lead role in preparing and implementing the design project, although most departments will be actively involved in all stages throughout ISU'92. For example, the Life Sciences department will be concerned with two areas of inquiry in connection with the project. One area relates to the health issues attendant to radio-frequency power beaming and what is currently known in this area. The other area relates to crew health and safety issues during the construction of space systems. Issues of frequency allocation and orbital slots will fall within the Space Policy and Law department. The Business and Management department will examine the financial considerations as well as the project management concerns of this international undertaking. The Physical Sciences department may choose to look at how large structures and high power may be enabling technologies for the space sciences as well as examining ways to mitigate potential deleterious effects of large scale space power collection and transmission to astronomy.

ISU'92 PROJECT OBJECTIVES

The design project proposed for the 1992 session will have the following elements:

- Multidisciplinary design study, to include financing, management and legal issues
- Multinational student and faculty approach

SSPP PROJECT SCOPE AND METHODOLOGY

An international advisory committee for the project is being created under the chairmanship of Dr. Peter E. Glaser. Faculty for the project will include a broad range of leaders from academia, industry and government agencies from around the world. This advisory committee will work with the executive staff of the ISU to formulate the project scope and methodology.

CONCLUSIONS

The ISU 1992 Design Project on the Space Solar Power Program should offer an unprecedented opportunity for its student and faculty participants to develop a synthesis approach to near-term and long-term space solar power production and distribution. The ISU'92 host country, Japan, is already supportive of the project, and international sponsorship of the endeavor is expected from both government and industry. Thanks to the international and interdisciplinary approach of the ISU, the results of the 1992 study - in the form of a Final Report and video animation- will form a useful resource for further SPS-related research and study in all nations of the world.

A8.1 Problems experienced by man when constructing giant structures in space

C.A. TIMSIT - MEDISPACE, Paris, France

SUMMARY:

In order to be profit-earning, those space structures should be very large. They will be assembled in space, as a giant Mecanno, using terrestrial or lunar materials. The construction and maintenance of these space systems, which can require one to five years, or more, rely on the ability of man to work outside tha spacecraft environment, using robot systems, teleoperator systems or telepresence systems, still to be demonstrated in space.

Completion of such giant structures in space required an unacceptable amount longer and longer EVA's. More, after the completion of the structure, many EVA's will be needed for maintenance tasks and for keeping the station in shape. The extra-vehicular activities we have experienced nowadays are under two spacewalks per mission, and consequences on man of repeated spacewalks are unknown.

We shall have to consider the biomedical variables which may be encountered by astronauts working for very long periods of time in the weightless environment.

Many advancements are necessary to improve the countermeasures: astronauts training in pools, parabolic flights and space suits and life support systems improvement. The recent Fisher-Price report (listing 100 recommended actions that can reduce the amount of maintenance) demonstrate that, by increasing the amount of maintenance that can be done with robots, and streamlining the tedium of human repairs, the number of spacewalks may be reduced in a proportion of five to one.

KEY-WORDS:

MANNED MANOEUVRING UNIT (MMU) - EVA'S - EXTRA-VEHICULAR ACTIVITY - GIANT SPACE STRUCTURES - LIFE SUPPORT SYSTEM - SPACE MEDICINE - WEIGHTLESSNESS - METABOLISM - PARABOLIC FLIGHT - NEUTRAL BUOYANCY TANK METABOLISM - COUNTERMEASURES.

RESUME:

Pour être rentables, Les Centrales Solaires Spatiales devront être très grandes. Elles seront montées dans l'espace, comme un Meccano géant, qu'elles soient construites avec des matériaux terrestres ou lunaires. Cette construction peut durer de 1 à 5 ans, voire plus, et la présence de l'homme lors de ce montage sera indispensable, quelle que soit le schéma utilisé: présence humaine sur site, télémanipulation par robot interposé ou conception et programmation de robots-ouvriers.

Pour monter une telle structure, les sorties dans l'espace devront être très fréquentes et de plus en plus longues. Une fois cette structure achevée, de nombreuses EVA seront nécessaires pour l'entretenir et la maintenir en bon état de fonctionnement. Or l'expérience dont nous disposons actuellement ne va pas au delà de deux sorties dans l'espace par mission, et on connait encore mal l'impact sur l'homme de sorties répétées.

Il nous faudra envisager les facteurs biomédicaux à prendre en considération chez des astronautes qui travaillent pendant longtemps dans un environnement microgravitaire.

Des progrès sont encore nécessaires pour améliorer les contremesures: entrainement en piscine des astronautes, vols paraboliques et amélioration des scaphandres et des équipements de support-vie. Les progrès de la robotique dans les prochaines années (Le tout récent rapport Fisher-Price dresse la liste de 100 recommandations pour réduire le temps de maintenance) montre qu'en augmentant le nombre de tâches effectuées par des robots, on pourrait réduire dans une proportion de 5 à 1 le nombre d'EVA nécessaires.

MOTS-CLES:

UNITE MOBILE MANOEUVRABLE PAR L'HOMME (MMU) - ACTIVITES EXTRA-VEHICULAIRES - STRUCTURES SPATIALES GEANTES - SYSTEMES DE SUPPORT VIE - IMPESANTEUR - MEDECINE SPATIALE - METABOLISME - VOL PARABOLIQUE - RESERVOIR A FLOTTABILITE NEUTRE - CONTREMESURES .

I - INTRODUCTION:

Construction of large multi purpose structures in Earth orbit is expected to be the goal of a number of future space programs. While mission planners are in the advanced stages of project analysis and design of large space systems, the era of the Space Shuttle enable applied testing of construction techniques, payload design and man-machine interface

In any case, the work of man in space is limitated by three factors: the first is due to the space environment, the second depends on the limits of life support systems, and the last one is due to the Human factor. It can be assumed that human operators will finallt work in conjunction with remote manipulators and robot assemblers for the successful construction of the space structures.

II - THE SPACE ENVIRONMENT:

Space represents a very unfriendly environment for astronauts, and they will have to live in space and work outside of their vehicle for long durations EVA's. They are then exposed to many problems in this new environment

1) Thermal Variations:

Thermal variations experienced by astronauts during an EVA reach about 250° within 90 min. (from -118° to +132°C according as you are facing the sun or in the shade of the Earth or the spacecraft).

2) Space Vacuum:

In space, vacuum is very close to absolute. It enforces a pressurization of suits and hatches. The difference of pressure between inside and outside the spacecraft reach about 1 atmosphere (as in a plane). The spheric or cylindric shape gives a better resistance to spacecrafts against space vacuum. Direct exposure of man to vacuum means an instant death.

This pressure is important in the determination of suit mobility.

3) Weightlessness:

Space Station, bounded to the laws of gravity, flies in weightlessness. So are the persons and objects on board, except if facing internal accelerations.

The effects of weightlessness on the body are numerous, and they cannot be detailed here: mineral loss of bones, cardio-vascular deconditioning, space motion sickness or amyotrophy. They could be avoided by creating an artificial gravity by rotating all or part of the station.

4) Mechanical laws:

In space, the station is bounded by vis inertiae and gravitation as any celestial body. Hand rails are necessary to perform any task, as for repearing an orbiting satellite.

5) Cosmic Rays:

The effects of cosmic rays on astronauts exist, but they are unknown in geostationnary orbits, where SPS will be fixed. On Earth, life is protected by a shield of one kilo of matter per cm2. In space, it is necessary to restore this safety device, to avoid radiation belts, and to keep out from sudden sun eruptions.

Most of our present knowledge on dosimetry and radiobiological findings in spaceflight radiation environment is based on experiments in orbits at 200 - 250 km, and inclinations of 28° to 58°. Risk is even more important in the higher orbits of manned space stations.

Estimated doses are:

Low Earth Orbit:	0.51 mSv/day
Space Station orbit:	2,90 mSv/day
Geostationnary orbit:	4,00 mSv/day

For a mission on a GEO, if we consider an altitude of 35.790 km, 0° orbital inclination and a parking longitude of 160° West, the dose equivalent for a 15 days mission is 7 mSv (0,7 rem). The galactic cosmic rays will add a dose of about 8 mSv plus the dose that will accumulate during traversal of the radiation belts as the spacecraft goes from low to high earth orbit depends of the length of the time to reach the GEO orbit altitude. A number of other factors will influence the time required to reach the GEO orbit. The worst case might add 20 mSv to the BFO dose on both the outward and return trips. Thus, the total dose equivalent for such a mission, and without EVA or SPE (Solar Particle Eruption) could reach about 60 mSv (6 rem).

Recommendations for the dose equivalent limits by the NCRP Committee 75 (1986) are (in Sv):

PERIOD	BFO	SKIN	LENS	GONADS
30 Days	0,25	1,50	1,00	0,25
Annual	0,50	3,00	2,00	0,50
Career	6,00	4,00	1,50	

6) Impact of Micrometeorite and Space Debris:

There is actually 50 to 70.000 space debris actually orbiting around Earth. Experts are worried that spacecrafts could be endangered by the increasing amount of artificial debris.

Experts say a pea-sized fragment orbiting at speeds over 20.000 km/h could shatter a large satellite or destroy a space suit.

7) Changes in the Sleep-Wake rhythm:

Astronauts have a good sleep in space. The lack of a 24 hour sleep wake rhythm or the rhythm of 90 min experienced in Earth orbit may, in long duration flights, generate psychological troubles.

III - EXTRA VEHICULAR ACTIVITIES:

1) IN-ORBIT SERVICING:

There are three groups of tasks which are performed in orbit during EVA's: some of them are planned (space systems construction, removal of materials produced on board); some are not (replace or reconfigure equipment in order to perform new functions and/or to extent mission duration); and some are unforeseeable (replacing failed items, inspect malfunctions or unexpected problems, safety operations).

In the broadest sense, servicing is taken to encompass a group of tasks (E. Olier) which are performed in orbit to:

* Remove materials produced onboard a spacecraft in order to return them to Earth;
* Replenish consumables in order to extent mission duration, proceed with space based manufacturing or continue with in-orbit experiments;
* Exchange crew for manned systems, including provision of consumables, such as oxygen, food or water;
* Replace or reconfigure equipment, including payloads, in order to perform new functions;
* Execute preventive maintenance;
* Inspect unexpected problems or malfunctions on suspect equipments;
* Replace and in-situ repair of failed items;
* Verify after the above tasks have been performed and re-activate systems.
* Servicing of space systems and satellites for maintenance and repair, or routining servicing.
* In-orbit experiments support, including retrieval and replacement of samples; products and equipment,
* Contingency activities for a very wide variety of missions,
* Construction activities for space stations, platforms and satellites.

2) BACKGROUND ON EVA OPERATIONS:

Since the first spacewalks carried out during VOSKHOD-2 and GEMINI-4 by LEONOV and WHITE in 1965, respectively, EVA has been a major element for the completion of the mission objectives of american and soviet programmes.

In 20 years, the duration of EVA's went from 12 min to more than 6 hours. Four kinds of EVA's can be described:

* Stand-up EVA: astronaut standing upright on his flight seat with only the upper half of his torso protruding from the depressurized vehicle;
* Umbilical EVA, astronaut making a complete egress from the vehicle, but remains connected to it by a tether.
* Lunar EVA: used during the APOLLO program, during lunar surface activities but not in a totally weightless state.
* Free-floating EVA, astronaut not connected to the spacecraft, using a MMU and a reusable life support system.

The in-orbit EVA operations demonstrated that the EVA provides a unique capability for both planned and unscheduled servicing modes, and for tasks to which the operations cannot per definition be automated.

The successful results in recent servicing missions will increase the use of techniques for intervention with in-orbit space systems. This confidence is also demonstrated by the present design of future space systems, which rely for their construction, operation and maintenance on the ability of man to work outside the spacecraft environment and on the capabilities of remote manipulation techniques (E.Olier).

Figure N°1:
EVA performed inside the Shuttle cargo bay: note handrails and handles used by astronaut to travel along the bay (NASA)

3) BIOMEDICAL PROBLEMS DURING EVA's:

Recent data have indicated that short duration EVAs revealed few major biomedical hazards to astronauts (Berry, Burns, Bellenkes, Johnson & Waligora), but there is a possibility to observe physiological anomalies during long EVA periods that could influence the ability for astronauts to maintain high levels of performance and efficiency.

The first EVA related biomedical difficulties were experienced by the GEMINI astronauts: stressing, sweating, overheating, difficulty in maintaining body attitudes, high level of heart rate (180 beats/min, or respiration rate (40/min). This was due to a high workload, a lack of preflight training and the bad equipment of those early EVA suits. During the SKYLAB program, body mass, heart rate and metabolic rates were recorded during all EVA periods. They were similar to those recorded during the APOLLO Lunar excursion EVAs. The mean metabolic rate was 230 kcal/h, but exceeded 500 kcal/h for the SKYLAB-2 commander while he attempted to deploy a solar pannel (Bellenkes, Waligora).

The construction of large space systems will involve a man-machine interface. The biomedical variables inherent to long duration EVAs could be the same as for short EVAs, but to a greater degree due to the increased work loads.

The question arises as to what extent the crewmen will either supervise construction via robot assemblers or will take part in beam assembly. Anyway, it would be much more feasible to maintain astronaut quarters in orbit at the construction point, rather than to continuously transport the crew from and to Earth.

4) EVA VS TELEOPERATION:

Candidate automated systems for space operations can be categorized as follow (E. Olier):

* robot systems, which can be considered as the technologies and devices for carrying out, under human or automatic control, physical tasks that would otherwise require human capabilities.

* Teleoperator systems, considered as the technologies and devices for the execution of physical tasks by a manipulator under human control. EVA's and telemanipulation operations rely on man for their accomplishment. And both are subject to man's limitation.

* Telepresence systems, which is a concept of remotely controlled manipulation whereby the manipulator at the work site has the dexterity to carry out normal human functions and the operator at the control site has sensory feedback sufficient to provide the feeling of being present at the remote site when the action is taking place.

The actual allocation of man and machine in space should be based on a rigorous understanding of the implicit capabilities and limitations of both man and machine, as well as of exhaustive analyses at mission, system, function and task levels (E. Olier).

5) THE EVA SYSTEM:

EVA's should be designed so that EVA time is crew limited, not hardware limited.

A) THE SPACE SUIT SYSTEM:

In the future, astronauts must be able to be exposed instantly to the space environment. In order to make this possible, advanced space suits have to be conceived, highly reliable, requiring little maintenance and being more comfortable than current suits. This suit should be designated to be put on and taken off in a few seconds, and it was to have an internal pressure of at least 8.3 psi which would have eliminated the possibility of the bends, and could reduce the pre-breathing time. Those suits will be equiped with life support systems with increased autonomy.

US astronauts used a IVA (Intra-Vehicular Activity) suit during MERCURY, GEMINI, APOLLO and SKYLAB programs to prevent a sudden depressurization of the spacecraft. With the Shuttle program, an EVA suit is used.

Soviet cosmonauts did not use ant suit untill the SOYUZ-11 accident. Now, they use a IVA suit for all the critical phases of the flight, and an EVA suit for EVA activities.

Both EVA suits are connected to pure oxygen at a reduced pressure: 0.3 bar for US and 0.4 bar for Soviet suits.

To prevent the risk of aeroembolism, it is necessary to reduce the partial pressure of the Azote in tissues. This can be done by two ways:
* Direct denitrogenation, by breathing pure oxygen before the EVA,
* Direct denitrogenation associated with a decrease of the spacecraft pressure.

This denitrogenation takes a long time, so that the EVA represents only a small part of the time used to make the EVA possible. THe only way to reduce the time lost is to increase the suit pressure. But it reduces the mobility of the suit and increase the risk of loss across suit joints: gloves, helmet, knee or elbow).

The answer can be found with a new generation of space suits, but this spacewalk crisis is compounded by last

year's cancellation of the advanced space suit for Freedom. The new suit was to have been highly reliable, requiring little maintenance and more comfortable Othan the current suit. The suit was designed to be put on and taken off in just a few seconds. The new suit was to have an internal pressure of at least 8.3 psi which would have eliminated the possibility of the bends. However, last year's budget cuts forced NASA to abandon the new suit design and to use the existing space shuttle suits for Freedom construction and maintenance. Using the space shuttle suit severely limits space station EVA's because spacewalks could only be made when a space shuttle was docked.

The space suit system must be designed to satisfy a number of key requirements:

* Crewmember protection:
In addition to provide radiation and thermal protection, the crewmember must be protected against the effects of vacuum through the provision of a pressurized environment within the suit. This pressure is important in the determination of suit mobility and is dependent upon the requirement to operate from a given mothercraft cabine pressure within a specified reaction time while observing oxygen toxicity and hypoxia limits, and limiting the risk of decompression sickness to an acceptable level. The space suit system must also protect the crewmember from the effects of micrometeorites and space debris such that the probability of suit puncture is considered sufficiently remote.

Figure N°2:
First EVA using MMU (Manned Manoeuvring Unit). Astronaut B. Mc Candless, STS-10, Feb. 1984 (NASA).

* Physiological support:
A circulating ventilation flow is required, in which the oxygen partial pressure, exhaled carbon dioxide partial pressure, humidity and contaminants are maintained at the required levels. As EVA sorties will typically last for several hours, food, drink and waste management facilities must be included.

* Performance:
The crewmember must have the mobility, reach, dexterity, tactile feedback and visibility necessary to accomplish efficiently the servicing tasks within his fatigue limitations. Communications capability both voice and video is required to support effective task execution.

* Accomodation:
To ensure crewmember comfort, the suit must be tailored to the individual's anthropometric measurements adjusted for zero "g" growth.

* Safety:
Safety is of paramount importance. Suit must therefore be fail-safe as a minimum such that in the event of failure, a safe return to the mothercraft is assured. Limited interface compatibility with US and Soviet systems are desirable to enable crew member rescue.

* Operations:
The suit system must provide the required protection and physiological support to sustain the number and frequency of EVA sorties envisaged. The reaction time between the need for EVA arising and airlock egress must be minimized as must the need for real time support by mothercraft and ground crew.

* External Interfaces:
The suit system must be compatible with the mothercraft airlock, utilities and cabine pressure. It must also be compatible with the access corridors contact temperatures, contamination levels and sharp edges both on the mothercraft and task object. In particular, glove dexterity must be adequate to ensure efficient use of servicing aids, hand rails and hand holds.

The in-orbit EVA offers an interactive resource which has proven to be a fundamental extension of the ground to the success of any missions, and has demonstrated that the EVA crew member provides a unique capability for both planned and unscheduled servicing modes,

and in particular for those contingency tasks to which the operations cannot per definition be automated.

Up to date, two factors can limit the duration and the frequency of EVA's: physiological limitation and technical constraint.

* Technical constraints have been largely developed : limited autonomy of actual life support systems, decrease spacewalking overhead (five hours of time spent to dress and undress the astronaut, prebreathing period, in order to perform one hour of work in space), important loss of time because the timing spent in EVA.

* physiological limitation: there is a limited ability for man to live and work in space; it is known that fatigue increase with degree of mental concentration. In an other hand, there is a risk of decompression sickness if prebreathing requirements are not respected. In order to improve this endurance, astronauts training methods must be improved (particularly simulation with parabolic flights and training in water tanks), robots and remote manipulation techniques should be more perfecting so that new elaborated robots will progressively replace man for repetitive tasks.

B) COUNTERMEASURES:

Countermeasures will be the most important point for the security of EVAs and they can be separated in two areas:

• Astronauts training: two ways are used to obtain conditions of free floating: the use of neutral buoyancy tanks and parabolic flights.

- Neutral buoyancy tanks are large pools filled with water into which the astronauts, with their EVA suit, the spacecraft mockups and the support teams are submerged. Due to the problems encountered during past simulations, engineers designed straps and grips for vehicle hulls which would provide the astronauts with firm boot and glove restraint during movements and work.

- Parabolic flights are performed by Air Force jet transports (KC-135) and pilots are instructed to fly in step parabolic arcs. At the peaks, passengers are able to experience the resulting negation of gravitational vectors as a brief (20") period of weightlessness.

* Another primary countermeasure against the adverse physiological effects of long duration EVA is the use of well designed and efficient garments (suit, gloves and helmet).

Beside the increased metabolism and muscular behaviour noted during EVAs, an overheating person, performing heavy tasks and not properly cooled, will increase oxygen consumption, produce more CO_2 as a function of increased O_2 intake, and will increase heart and respiratory rates. There is also a risk of being hurt. During a soviet EVA, cosmonauts reported that their arm muscles were tired, probably because their were constantly stained to keep the body in a fixed position (Grigoriev) During the next EVA, they used a special device for that purpose and their arm muscles were less strained and tired.

The other risks of EVAs are: fire, explosions, injuries, illness, vomiting,

Figure N°3:
Underwater work using the standard space suit of the Shuttle in the MacDonnell Douglas EVA simulation tank (AW & ST).

nausea, associated to space motion sickness or space adaptation syndrome, collision with a natural or artificial space debris, loss of pressurization, electrical shock, exposure to cosmic rays, and sudden changes of orbits.

LIMITS OF EVA'S:
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Watters and Stokes (1979) have reported that in a series of experiments conducted at the Marshall Space Flight Center's neutral buoyancy tank, pressure suited astronauts could move and position a 17.000 lb structure with only minor difficulties. With coordinated

movements by each team member, the unit was placed in a target structure with minimal energy expenditures. Of course, in later studies, it was also found that the manipulation of large beam structures proved more effective if done with machine assistance (less energy expended to complete the task than if done with more than one human participating). So very large placements could be accomplished effectively and with low energy expenditures by a team of engineers while the smaller tasks involving the assembly of less massive components could best be done by a single person with remote manipulator arm assistance. The key here is to expend as little energy on a given task as is possible.

MAN OR ROBOT ? THE NASA POLICY.

A recent decision has been taken in USA to require private financing for several NASA projects threatens to derail a contract to build a robotic unit for space station assembly. Two companies, Grumann and Martin Marietta, have submitted bids to build the servicer. Besides this decision, NASA scientists are developing a telerobotic system to automate assembly of large space structures including satellites, polar platforms and antennas.

Anyway, robot systems can perform, under human or automatic control, physical tasks that would otherwise require human capabilities. Teleoperator systems is a device for the execution of physical tasks by a manipulator under human control.

EVA and telemanipulation operations rely on man for their accomplishment. Both are subject to man's limitation. It is well known that fatigue increase with degree of mental concentration, and in this respect, telemanipulation tends to increase the human fatigue at work.

Those private fundings will be used to bring some advanced projects to a successfull issue: perfecting robotic fitting used for constructing the Space Station, preliminary studies for Space Power Stations, mockup Spacehab-like allowing long duration missions for the Space Shuttle.

In United States, the Department of Energy, the Department of Defense & NASA will spend about 400.000 US dollars to end the project of GENERAL ELECTRIC in 1994.

The following pictures illustrate two major projects in this area: GRUMANN and MARTIN MARIETTA.

Figure N°4:
GRUMANN's concept of the robot allowing NASA to reduce the number of astronauts EVA hours needed at the Station. AW & ST

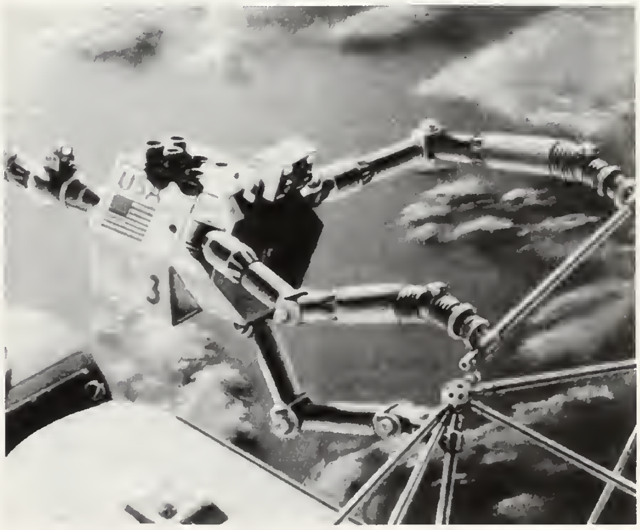

Figure N°5:
A robotic servicing unit used for Space Station assembly is depicted here in a MARTIN MARIETTA artist concept. AW & ST.

THE EUROPEAN POLICY:

Getting mastership of space without the help of robotics is quite impossible because space is an unfriend place for men. Three kinds of robots can be considered:

- Space probes for interplanetary missions;
- Small autonomous shuttles used to examine the Space Station, or to travel through relatively short distances;
- Manipulator robots used to fit together giant structures in space.

Many projects of this kind exist in United States or in Europe. General

Electric in USA and The Commissariat à l'Energie Electrique (CEA) in France work on a tog-robot for space.

Between 1982 and 1986, CEA spent 12 millions of French Francs to develop a new program called ERATO. A contract signed with the CNES allowed to assume the financing of complementary studies from 1986 to 1989 with a budget of 36 millions of French Francs: 50% from the CEA and 50% from the CNES.

Other kinds of robots will be confined to assist astronauts in many tasks, so that they can assume maximum work in minimum time. Man will stay close to operating levels, and will control every operation on a TV screen.

European Space Agency commited three european industrials involved in the space adventure to study and realize the framework of the HERMES robotic arm: MATRA Espace, MBB ERNO and FOKKER. All of them are well familiarized with the constraints of weightlessness.

MEN AND/OR WOMEN ?

Candidate Astronauts selected for this kind of work must be very specialized because they must be able to face to any unprevious situation. Those engineers will have to repear broken or defectuous satellites or to put together giant structures in space. They will be helped by ground technicians who decide the kind of intervention after analyzing the problem and interroging the software in the computer.

In many cases, and problems experienced on Space Shuttle flights or Space Stations SKYLAB, SALIOUT or MIR confirmed it, they will have to change a chip or an electronic card, or even to kick a failing system. Old stagers of space know well how to use it, even if they didn't learn that when training.

Moreover, even if those motions are very simple, a robot is absolutely unable to accomplish them because we don't know yet how to program the "D-System". And this a reason of the need of man in space.

CONCLUSIONS:

Many advancements are yet necessary in the areas of astronauts training in neutral buoyancy tanks and parabolic flights, and in space suits life support systems improvement.

The recent FISHER-PRICE report lists 100 recommended actions which, by increasing the amount of maintenance that can be done by robots, and streamlining the tedium of human repairs, may reduce number of spacewalks in a proportion of five to one.

We can also certainly draw lessons from the experience of undersea workers who are confronted every day to many of the problems encountered by astronauts working in space.

At end, the adverse effects expected during long-duration extra vehicular activities can be minimized by the use of pre-flight simulation training, upgraded life support systems capable of handling heavy physiological loads, adequate crew housing, good work-rest period scheduling, and mechanical assembly aids such as teleoperated devices and personal maneuvring units.

The successful development of an EVA space suit system will be a technological challenge of the first order as it requires many diverse skills to be brought together in a coherent technological drive.

However, in a number of key areas, the magnitude of the development task required to fulfil the needs of EVA is large and should not be under estimated.

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A8.2 The effect of human productivity in space construction on SPS transportation costs

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Absract

This article examines the relation between different methods of launching and of orbital construction of the SPS. Tests on human assembly, conducted in neutral buoyancy and in space, showed that the cost of construction in orbit will be a relatively small component of the total cost of transportion and assembly. The presentation includes a short film of these tests

Résumé

Cet article examine la relation entre différentes méthodes de lancement et la construction en orbite du SPS. Des essais sur l'assemblage par l'homme, conduits en équilibre hydrostatique et dans l'espace, montrent que le coût de la construction en orbite sera seulement une relativement petite partie du coût total de transport et d'assemblage. La présentation est accompagnée par un film court de ces essais.

Introduction

The economic viability of the SPS will depend largely on the costs associated with its construction in orbit, primarily the cost of transportation to LEO (Low Earth Orbit), which is expected to account for the major part of the total costs. Three independent studies conducted during the 70's (Refs 1,2,3) found that there were no serious operational or ecological problems associated with the SPS, but focused on costs as a major factor in determining whether to recommend the initiation of an SPS development program.

During the same period studies were conducted at MIT (Refs 4,5) on the optimum size of the required launch vehicles and on human productivity in orbital construction. The structure of the very large platform, and the consumables and life support required for the personnel to assemble it, make up the bulk of the transport requirements to LEO. If productivity were high, existing vehicles could be used to transport smaller elements of the structure for assembly in LEO. If productivity were low, larger components of the stucture would have to be assembled on the ground, and placed in orbit by a heavy lift launch vehicle (HLLV). Initiation of an SPS program would then have to be delayed until such a vehicle were operational.

Early experiences with EVA (Extra Vehicular Activity), particularly in the assembly of the sunshade required on Skylab after failure of one of its solar panels to deploy, led to the conclusion that human productivity in orbit would be very low. The Space Systems Laboratory (SSL) at MIT, largely staffed by would-be astronauts, was unwilling to accept this conclusion and a program was therefore initiated in 1975 under NASA sponsorship in an attempt to obtain quantitative information on human productivity in a simulated space environment. The program culminated in 1985 in the EASE experiment (Experimental Assembly of Structures in EVA), conducted in space during the STS 61B mission. This paper will review results from this program briefly and their potential impact on SPS transportation and assembly costs.

Transportation Costs to LEO.

As is the case for most transportation systems, low costs are associated with a large fleet operating at high frequency, thus offering a high level of service (LOS). Direct costs are thereby reduced because non-recurring vehicle development costs are amortized over a large number of vehicles and recurring production costs benefit from the powerful effects of learning (Weber-Fechner law). As an illustration, Fig.1 shows the effect of

this logarithmic reduction on the historical maintenance costs of the DC family of aircraft. A similar trend was apparent in the operating costs of Columbia until the Challenger accident put a temporary stop to the program.

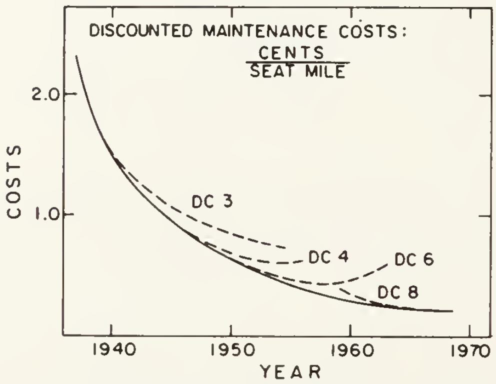


FIG. I MAINTENANCE COST HISTORY OF DC FAMILY OF AIRCRAFT

A high LOS also reduces Indirect costs, which typically account for about 50% of the total operating costs of air transport systems. Landside, mission support and personnel costs are reduced by virtue of the more efficient use of ground facilities with the higher frequency of service.

To be economically viable, a high LOS requires a high demand. Transportation demand is usually a secondary, or derived demand (required travel derived from some need other than the joy of travelling), changing only slowly as market forces dictate. There are some exceptions, as in the case of a less derived demand such as travel across the North Atlantic, much of which is conducted for the sake of travel. Clearly, for the forseeable future, space travel will remain a derived demand and will grow slowly as the industry matures, although the process is synergistic in that costs will decrease markedly with growth which will, as in the case of air transportation, stimulate further growth. Certainly the potential demand for space transportation is almost unlimited if we are to preserve our quality of life and help the developing countries to approach this same quality.

However, a more pragmatic approach to transportation costing as a function of scale would suggest that operating costs may best be analysed using, as an additional parameter, levels of fixed demand rather than assuming that demand will grow as the payload capability of the vehicle increases. The difference between these two approaches is apparent from Figs.2 and 3 taken from some early studies (Ref.4). The shuttle payload of 50,000 lbs is close to the optimum for a demand corresponding to 0.1B lbs, of the order of one SPS. These predictions have been periodically updated (Refs 6,7) as detailed information on actual costs of the shuttle, and of other operational

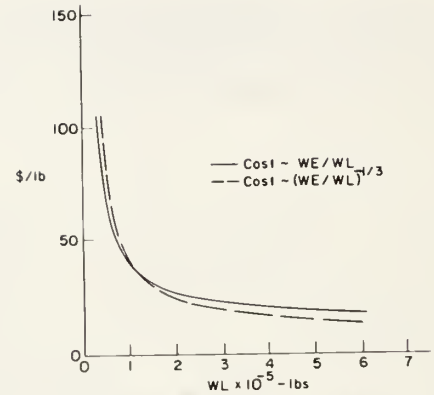


Fig. 2 Direct operating cost, in \$/lb to LEO, as a function of payload weight WL for unlimited demand.

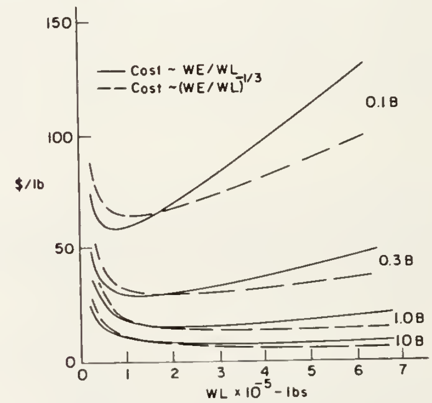


Fig. 3 Direct operating cost, in \$/lb to LEO, as a function of payload weight WL for various demands, expressed in billions of pounds to LEO.

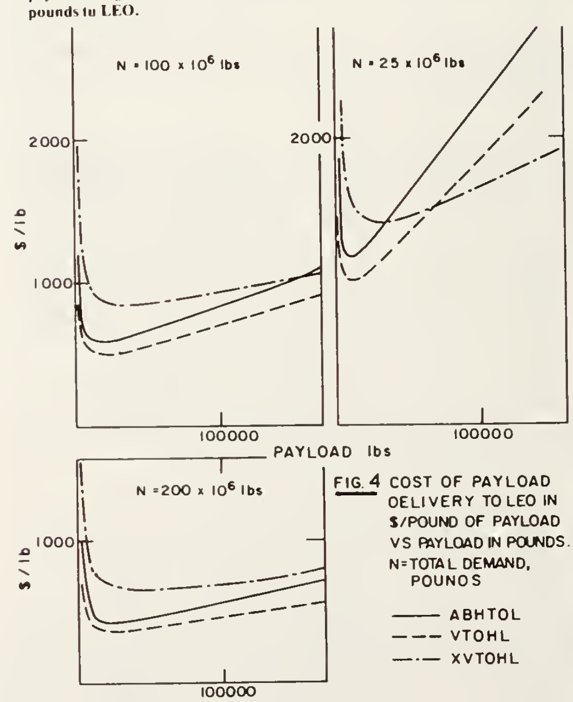


FIG. 4 COST OF PAYLOAD DELIVERY TO LEO IN \$/POUND OF PAYLOAD VS PAYLOAD IN POUNDS. N=TOTAL DEMAND, POUNDS

—— ABHTOL
– – – VTOHL
–·– XVTOHL

ABHTOL -- FULLY REUSABLE, AIR-BREATHING HORIZONTAL TAKEOFF AND LANDING: TWO-STAGE, BOTH STAGES WINGED. SECOND STAGE USES ROCKET ENGINES

VTOHL -- FULLY REUSABLE, VERTICAL TAKEOFF AND HORIZONTAL LANDING AS IN ABHTOL, BOTH STAGES ROCKET-POWERED.

XVTOHL -- VERTICAL TAKEOFF: THREE-STAGE ROCKET PROPELLED WITH THE FIRST TWO STAGES EXPENDABLE AND A THIRD STAGE REUSABLE UNPOWERED AND CAPABLE OF HORIZONTAL LANDING WITH FULL PAYLOAD.

launch systems, became available. Fig.4, taken from Ref.6, is an example of some later results for a series of candidate launch concepts. Evidently a rational development of new launch systems should be paced by growth in demand and, in particular, advances in technology.

For example, the NASP program has now advanced to the point where an air-breathing single stage to orbit (SSTO) vehicle, with its advantages in operational efficiency, greatly reduced indirect costs (possibly at some penalty in direct costs), and improved environmental impact, has become an option for the next generation of launch vehicles. Design optimization of this concept is a difficult and lengthy process. For the first time in the history of flight vehicle design the propulsion system, aerodynamic configuration and structure are fully integrated and inter-dependent. The engine diffuser and nozzle are part of the fuselage, which contains the fuel tank and useful load. The diffuser efficiency, which now affects not only specific impulse but also vehicle L/D, depends on vehicle attitude, hence on wing loading, hence on flight trajectory and, above all, on aerodynamic heating and the thermal protection system (TPS). The problem is compounded by the paucity of experimental data on the scramjet operating limits.

Fig. 5 shows a minimum fuel SSTO trajectory in which thermal constraints have been relaxed. Fig.6 is a minimum heat load trajectory. Minimum fuel load implies acceleration at maximum thrust which, for the scramjet, occurs at low altitude. Minimum heat load, on the other hand, requires acceleration at high altitude. In these examples, the assumed acceleration limit was 2g, the maximum engine pressure was 2 atmospheres, and the minimum engine pressure for sustained combustion was 1/2 atmospheres, setting the switch to rocket propulsion. Turbo accelerators were used up to M=5. Initial

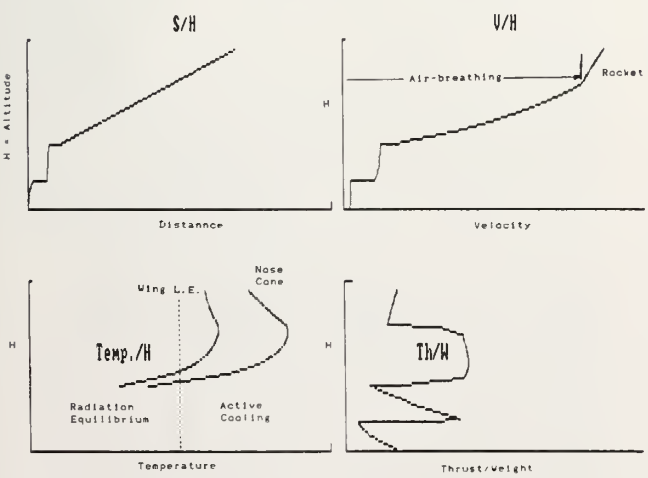


Fig.5 An optimized trajectory to orbit with relaxed temperature constraint. Sum of TPS penalty and fuel load = 0.60 of GLOW.

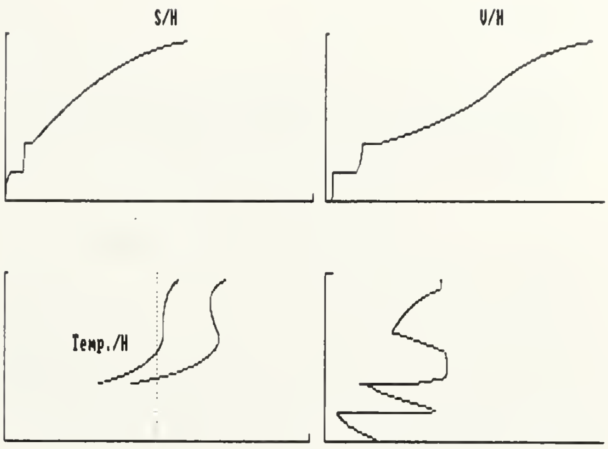


Fig.6 A minimum heat load trajectory. Sum of TPS penalty and fuel load = 0.71 of GLOW.

scramjet Isp was 2400 and the final value was 1000. Active cooling would be required, probably in both cases, for complete reusability. The sum of TPS load penalty and fuel load, shown in Figs 5 and 6 as a function of gross lift-off weight, indicates that, for this set of assumptions, the hot trajectory would be the preferred choice.

This simple example illustrates one of the many complexities in selecting an optimum SSTO configuration. In the face of these design challenges it is most probable that heuristic as well as formal optimization techniques will be required. Eventually a global optimization will have to be achieved through many design iterations with a performance index which includes all costs, direct, indirect and environmental. As was the case in the early days of aircraft design, many prototypes may have to be developed before full scale production is initiated. Such a development program is probably beyond the capabilities of any single organization or possibly even nation, and it is fortunate that the world wide interest in advanced launch vehicles seems to be producing promising new candidate concepts, such as Hermes, HOTOL, Hope, and Sanger II.

Clearly the technology is advancing rapidly and there is a growing choice of possible launch systems which could eventually ensure low cost access to space. However, at least initially, these new launch systems will probably have limited payload capacities, depending on demand. The 10 to 50 thousand tons or so projected for each SPS would ensure a large demand, and could well drive the choice of launch systems. The next section will examine whether SPS design, in particular the structural assembly techniques, would require vehicles with payload capacities larger than those suggested by the minimum cost trends of Figs 3 and 4.

Productivity in Orbit.

Three candidate methods for assembly in orbit of the very large structures which will be required for the SPS are:

1) Human EVA assembly,
2) Robotic assembly,
3) Self deploying systems.

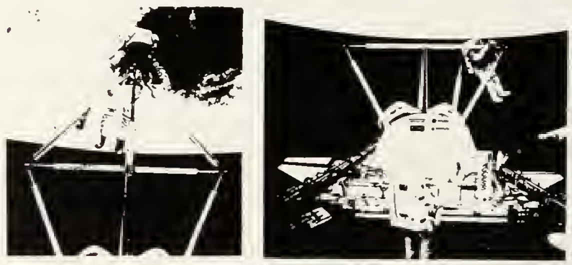
(1) has the advantage of greater flexibility in design options and choice of launch vehicles in that the components of the structure may be made small enough to fit in, for example, the shuttle cargo bay. However early experiences with EVA operations indicated that assembly by humans in orbit would be difficult and time consuming, leading to very low productivities and hence high costs. The major cost in maintaining personnel in space is that of transporting to orbit consumables such as food, water and oxygen, requiring a daily supply of at least 5 kgs per person working in space.

Based on the experience gained with EASE, a permissable working schedule would be 6 continuous EVA hours on alternate days. Typical productivities on Earth are about 1 kg/hr in complex operations such as aerospace manufacturing and 50 kgs/hr in construction work. Allowing 100% overhead for support personnel, the lower number would therefore increase the cost of transportation to LEO of the structure and crew to assemble it by a factor of over 4, a prohibitive increase. The higher number would indicate that human productivity was not a major cost issue. The incentive to quantify assembly costs in orbit was therefore strong.

Consequently, in 1975, an analytical and experimental program was initiated by the SSL under NASA sponsorship in an attempt to obtain information on human productivity in a simulated zero g environment, starting in the MIT swimming pool and progressing to the Neutral Buoyancy Facility (NBF) at NASA MSFC (Ref.8). Tests were also conducted, during parabolic maneuvers in the KC135 flight laboratory at NASA JSC, in support of analytical studies of the effects of water drag and apparent mass on the validity of the NBF simulation (Ref.9).

The results of these tests were unexpected in that productivities were found to be surprisingly high, with very rapid learning (slope of the order of 65%). Productivities were initially over five times that for similar assemblies performed on land. Mass assembled per hour was selected as the measure of productivity since the major effort involved was beam rotation and alignment.

Because of the significance of these conclusions for orbital assembly in general, including that of the space station, and because of remaining doubts as to the fidelity of neutral buoyancy simulation of the space environment, it was decided to conduct one of the experiments, the repeated assembly of a simple tetrahedron, in space (Fig.7) during the STS 61B mission, flown in November 1985. The results, for example those shown in Fig.7 taken from Ref.10, validated the NBF simulation and showed that EVA operations were in general slightly faster than in neutral buoyancy. As in the NBF tests, learning was rapid. Initial productivities were of the order of 800 kgs/hr, increasing some 50% after 4 assemblies. In projecting these results to predictions for future orbital construction scenarios, it should be noted that these test were conducted with highly trained and motivated subjects,



EASE Baseline Experiment

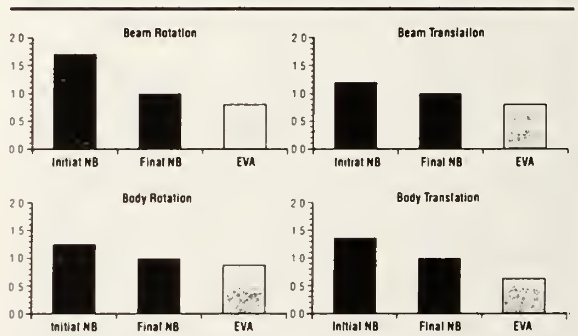
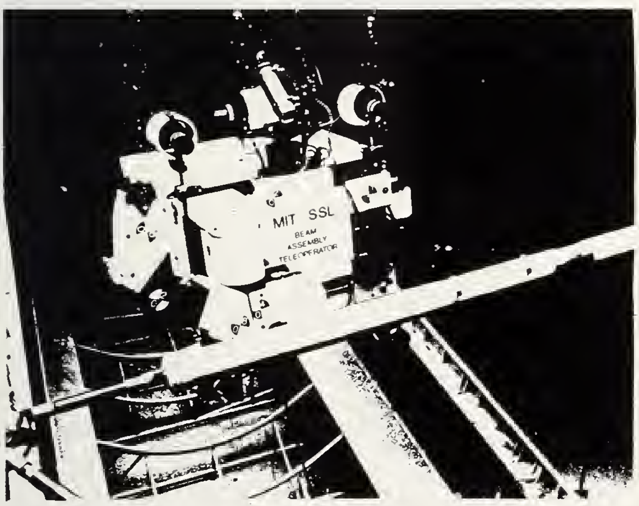


Figure 7: Part-Task Time Correlations
Normalized to Final Neutral Buoyancy Performance

working in new and stimulating environments. Nevertheless, the results are sufficiently conclusive to suggest that EVA assembly of an SPS in orbit will probably represent less than 1% of the cost of its transportation to LEO. Launch systems could therefore be sized for payloads close to the optima for the expected demand levels. The high utilization required by an SPS program will rapidly reduce transportation costs, benifiting all potential space programs.

A parallel program, also flown on STS 61B, involved tests on a NASA Langley partially deployable stucture (ACCESS). A direct comparison between the two methods of assembly, manual vs deployed, is not possible since the ACCESS structure had half the mass of the EASE structure and was more complex, resulting in half the kgs/hr but requiring less human effort, and therefore being less tiring (Ref.10).

Finally, robotic assembly remains an option, most probably a requirement if assembly were to be attempted in the high radiation environment of GEO. The ARAMIS program (Ref.11) indicated that robotic assembly could be competitive with human assembly for repetitive tasks. NBF tests with MIT's Beam Assembly Teleoperator (BAT), shown in Fig 8, indicated that a highly trained operator using a master/slave system from a remote control station could equal the productivity of direct human assembly of the EASE type stucture (Ref.12). However, in the absence of a fixed reference, the operator had to contend with two independent masses each with six degrees of freedom. A form of "vertigo" then developed. This could cause problems during the initial phases of construction before a partially assembled structure had sufficient mass to supply a relatively fixed reference. Research on robotic assembly in the absence of gravity is at an early stage and certainly more advanced concepts using expert systems, possibly with learning, could change these conclusions radically.



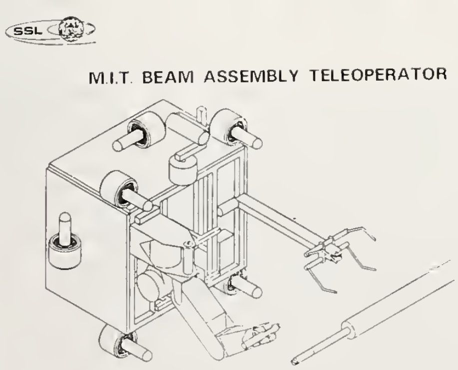


Figure 8

Conclusions.

Construction of the SPS in orbit by any of the three methods considered in this paper, human, robotic, or deployable, would represent only a small fraction of the total cost of its construction and transportation to LEO.

Implemenation of an SPS program is not dependent on the prior development of a new transportation system to LEO.

The transportation system, and the SPS structure, may be seperately optimized, with the former paced by technological advances and expected demand, and the latter by the preferred assembly scenario.

Direct EVA assembly is an immediately available option and probably the most efficient and versatile of the three methods considered.

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A8.3 Solar-pumped solid state lasers for space - Space power transmission

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ABSTRACT

Comparison of different laser types indicates that solar pumped solid state lasers are the best choice for space-space power transmission, taking into account the conversion efficiency of solar into laser radiation, the system masses and suitable laser energy converters. Therefore solid state lasers will be discussed in more detail with regard to system efficiency and thermal problems. The overall system efficiency can be improved by using different parts of the solar spectrum for laser pumping and for solardynamic or photovoltaic conversion. Experiments with direct solar pumped Nd:Cr:GSCG and Nd:YAG lasers at 77 K and 300 K show that cooling the laser crystals to temperatures much lower than 300 K reduces the thermal problems, increases the efficiency and improves the beam quality.

RESUME

Une comparaison de divers types de laser indique que le premier choix en ce qui concerne la transmission d'énergie dans l'espace revient aux lasers solides à pompage solaire; ceci en tenant compte du rendement, de la conversion de radiation solaire en radiation laser, de la masse du système ainsi que des convertisseurs d'énergie appropriés. Pour cette raison, le cas des lasers solides sera discuté de manière plus détaillée sous l'angle du rendement du système et des problèmes thermiques. Le rendement global du système peut être amélioré en utilisant des parties distinctes du spectre solaire pour le pompage optique du laser et pour la conversion d'énergie soit photovoltaïque soit à base de la dynamique solaire. Des essais avec des lasers solides Nd : Cr : GSGG et Nd : YAG à pompage solaire direct ont été effectués à des températures de 77 K et 300 K. Il en découle qu'un abaissement de la température des cristaux lasers bien en-dessous de 300 K réduit les problèmes thermiques tout en accroissant le rendement, et la qualité de faisceau.

I. Introduction

Laser power transmission in space may play an important role in the future. Depending on the system design a number of power satellites which convert solar energy into laser energy, beam this energy continuously to satellites or space platforms so that no solar panels or batteries are necessary. Therefore, in low earth orbits (LEO) the drag problem is reduced, thus, compared to conventional space crafts, lower masses and longer lifetimes may be expected. Lower costs for space-space laser power transmission systems can be expected, as a comparison with solar photovoltaic systems showed.[1]

An additional advantage of a space-space laser power transmission system is that it can be a precursor to a space-earth energy supply system.[2] Also, if a laser satellite is available, it may be used for laser thermal propulsion or debris removal.[3,4]

In all of the above mentioned cases a highly efficient reliable laser with good beam quality is a must. We therefore started our work with selecting an appropriate laser source with regard to solar into laser radiation conversion efficiency, expected system masses and suitable laser to electrical energy converters. The results are given in chapter II.

A possible way to increase the overall system efficiency of solar pumped solid state laser power satellites is discussed in chapter III. Because it is well known that high power solid state lasers have thermal problems, we performed experiments with direct solar pumped Nd:Cr:GSGG and Nd:YAG lasers at 77 K and 300 K (chapter IV) to find out, if cooling can help to reduce these problems. Chapter V summarizes the results and gives an outlook on future work.

II. Selection of laser source

Many laser sources, using the sun as the primary energy source, have been discussed in the past for space power transmission.[2,5-18] They can be grouped according to their excitation mechanism into electrically, thermally and optically excited lasers. The first two laser types can be described as indirect solar pumped because they need to convert solar radiation into electrical or thermal power.
In contrast the third laser type, the optically excited lasers are direct solar pumped lasers. We do not want to repeat the discussion about the advantages and disadvantages of the different lasers which can be found in the cited literature. As selection criteria we use the overall solar into laser power conversion efficiency and the masses of the total laser system as they are given in the references or have been estimated by us. The obtained values are summarized in tables 1 and 2.

Table 1: Solar to laser efficiency

Laser source	Wavelength in µm	efficiency in %		
		intrinsic	electric	solar-to-laser
Electrically excited*				
KrF	0.248	10	2.5	0.4
Cu	0.510/0.570	3	1.4	0.25
Diode array	0.8	30	30	6
Diode pumped Nd:YAG	1.06	30	10	2
CO_2	10.6	13.7	5.5	0.88
CO	5.0	20	8	1.3
Thermally excited				
CO_2	10.6			0.2-15
Optically excited				
CF_3I	1.31			0.5
Nd:Cr:GSGG	1.06			2.5

* 20% efficiency for solar radiation into electrical power

Table 2: Total masses of a 1 MW laser system

Laser source	Masses in t					
	Solar cells	Concen-trator	Laser	Radiator	Beam delivery system	Total
KrF	1900		25*	170	1	2096
Cu	3130		25*	290	4	3449
Diode array	125		25*	27	10	187
Diode pumped Nd:YAG	380		25*	108	16	329
CO_2	860		20	57	1600	2540
CO	590		17	41	355	1003
CF_3I		15	31	16	24	86
Nd:Cr:GSGG		3	25*	94	16	138

*assumed value, see text.

Efficiencies higher than 1% can only be expected for the laser diode array, the diode pumped Nd:YAG laser, the CO laser and the direct solar pumped Nd:Cr:GSGG laser according to table 1. The possibly high value for the thermally pumped CO_2 laser must be treated carefully because this is to our knowledge a theoretical value and up to now not confirmed experimentally.

Examination of table 2 shows that there are only four laser systems with total masses expected to be well below 1000 t. These are the laser diode array, the diode pumped Nd:YAG laser, the CF_3I laser and the Nd:Cr:GSGG laser. For some of the laser sources we have taken a value of 25 tons (see "laser" in table 2) based on the assumption that the laser masses are not very different. The total masses show that even a factor of 10 in the laser masses does not change the overall picture. It is clear that one has to keep in mind, that a mass extrapolation for a laser of, e.g. some ten watts output power to a 1 MW laser is always problematic. Not mentioned in table 2 are the thermally excited CO_2 lasers because the system mass is dominated by the mass for the beam delivery system. Therefore their masses can be expected to be in the order of 2000 tons (compare table 2 for the electrical CO_2 laser).

A comparison of tables 1 and 2 shows that low efficiency or long laser wavelength are mass drivers. Clearly the laser diode array, the diode pumped Nd:YAG laser and the Nd:Cr:GSGG laser seem to be the best choice.

For space-space power transmission conversion of laser power into electrical power is necessary. A lot of conversion mechanisms and converters have been discussed.[19-21] Among them the silicon cell looks very attractive because its band gap fits very well to the 1.06 µm laser radiation. Two of the lasers selected above, the diode pumped Nd:YAG and the Nd:Cr:GSGG emit this wavelength. Therefore a combination of these lasers with silicon cells results in a conversion efficiency of about 50%.[20] Comparing these two lasers, the direct solar pumped Nd:Cr:GSGG is the best choice for space-space power transmission, because according to tables 1 and 2 it has a higher efficiency and a lower system mass.

III. Overall system efficiency

Talking about a laser power satellite for space-space power transmission, it is quite clear that onboard electrical power is needed for communication, for driving motors, etc. This problem can be solved by splitting the solar spectrum into two parts as shown in figure 1 in a schematic representation. The small mirror of the Cassegrain system has a partly reflective coating which reflects the useful part of the solar spectrum for laser excitation and transmits the remaining part to a solardynamic system.

We discuss this solution with respect to the selected direct solar pumped Nd:Cr:GSGG laser. The experimental solar into laser power conversion efficiency is 2.5% (table 1). This value may increase to about 8%, if the thermal problems can be solved (see chapter IV for discussion).[22] The useful part of the solar spectrum for the excitation of the laser is roughly between 400 nm and 700 nm. This spectral range contains about 38% of the total solar power.[23] Thus the selective solar-to-laser efficiency is 21%. The remaining 62% of solar power can be converted with an efficiency of 30% to electrical power by a solardynamic system with a high temperature gas turbine.[24] The efficiency of the solardynamic system with regard to the total solar spectrum is then 19%. So we have an

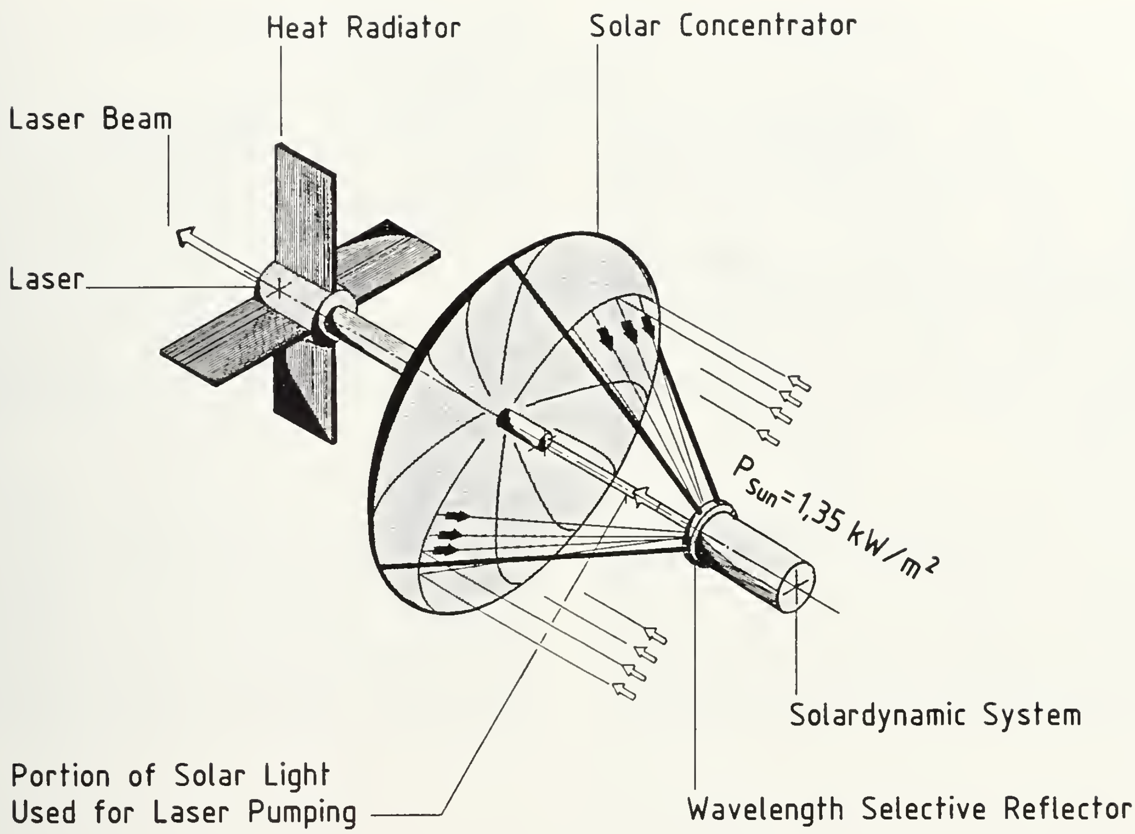

Figure 1: Schematic representation of the solar pumped space based laser system

overall system efficiency of 27%, a quite reasonable value. If not all the electrical power is consumed by the power satellite, the remaining energy can be used for example to run diode pumped Nd:YAG lasers.

The same discussion with respect to dividing the solar spectrum into three parts - for laser excitation, for solardynamic and for photovoltaic conversion - gives the following values:

- Direct solar pumped Nd:Cr:GSGG, see above
- Photovoltaic conversion with silicon cells:
  - 700-1050 nm useful part of solar spectrum containing 25% of solar power,
  - 35% mean conversion efficiency,[20]
  - 9% efficiency with respect to the total solar spectrum.
- Solardynamic conversion:
  - 37% remaining solar power, with the above values giving 11% conversion efficiency with respect to the total solar spectrum.
- Overall system efficiency: 28%.

The 4% relative increase of the overall system efficiency compared to the laser/solardynamic system cannot justify the much higher technical expense. If no solardynamic system can be used on the power satellite it can be simply replaced in fig. 1 by a photovoltaic system. In the latter case an overall system efficiency of about 17% can be expected with Si-cells.

For a detailed system optimization also other possible ways to split the solar spectrum have to be considered. The principle discussion we made shows that the overall system efficiency can be drastically increased if the solar spectrum is divided into different parts for different users. The estimated values are 27% for the laser/solardynamic system (described above) and about 17% for the laser/photovoltaic system.

IV. Experiments

As mentioned in chapter III solid state lasers have thermal problems, especially at high continuous output powers which are of course needed for space-space power transmission. These problems arise from the fact that at best 21% of the used solar energy is converted into laser energy (see chapter III) in the case of Nd:Cr:GSGG, and that the remaining solar energy is mainly converted to heat in the laser crystal. This heat generates effects like thermal lensing, stress induced birefringence, fracture of the

crystal etc., thus nearly all performance parameters and the reliability of solid state lasers are influenced.

A possible way to overcome this drawback is cooling of the laser crystals because the heat conductivity increases drastically with decreasing temperature.[25] On the other hand, low temperatures, e.g. 77 K, normally increase the heat exchange area and are therefore at least a mass driver. But, as we have shown in chapter III, a large amount of electrical power may be available on the laser power satellite so that cooling mechanisms, like the magnetocaloric effect, could be used to achieve an optimum regarding heat exchanger area and crystal temperature.[25]

Because of this situation we decided to perform experiments with direct solar pumped solid state lasers at 300 K and 77 K. In addition to the Nd:Cr:GSGG we also used Nd:YAG laser crystals. The Nd:YAG is up to now, to our knowledge, the only high power CW (1.8 kW) solid state laser that is commercially available. So a comparison of these two lasers is of interest and therefore the experiment was optimized not according to output power or efficiency, but according to the performance of the laser crystals at room temperature and at liquid nitrogen temperature.

The experiments have been performed at the solar furnace of the Weizmann Institute of Science, Rehovot, Israel. Figure 2 shows the experimental set-up including the flat heliostat, the 7 m diameter primary concentrator and the measurement systems. In figure 3 the laser cavity can be seen in more detail with the CPC (Compound Parabolic Concentrator), the cooling system for water (300 K) and liquid nitrogen (77 K), respectively, and the liquid filter used to avoid solarization of the laser crystals. A more detailed description of the experimental set-up and the measuring procedure is given in reference 26.

The results are summarized in figure 4. It can be seen that lowering the temperature from 300 K to 77 K not only decreases the laser threshold, but also increases the laser output power and the conversion efficiency. In addition, Nd:Cr:GSGG performs at 77 K better than Nd:YAG in contrast to 300 K. But the results show that Nd:YAG may also be an interesting candidate as direct solar pumped solid state laser, especially if

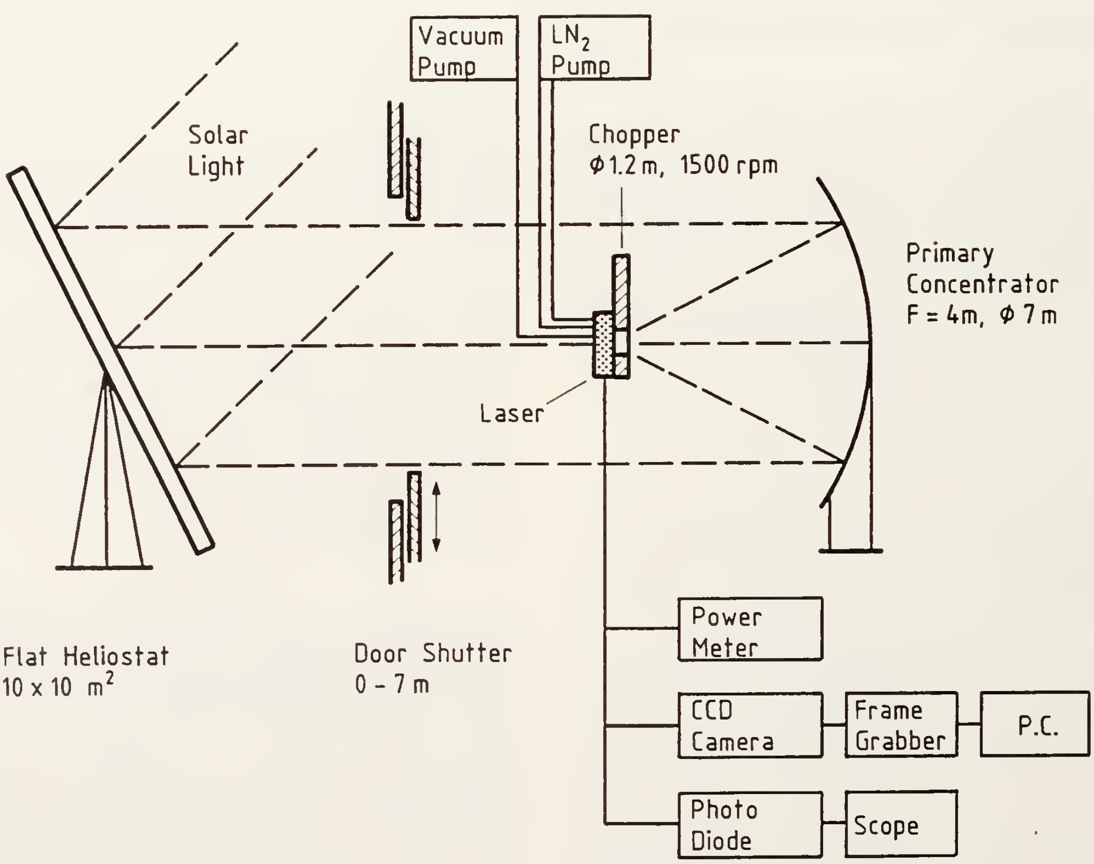

Figure 2: Experimental set-up

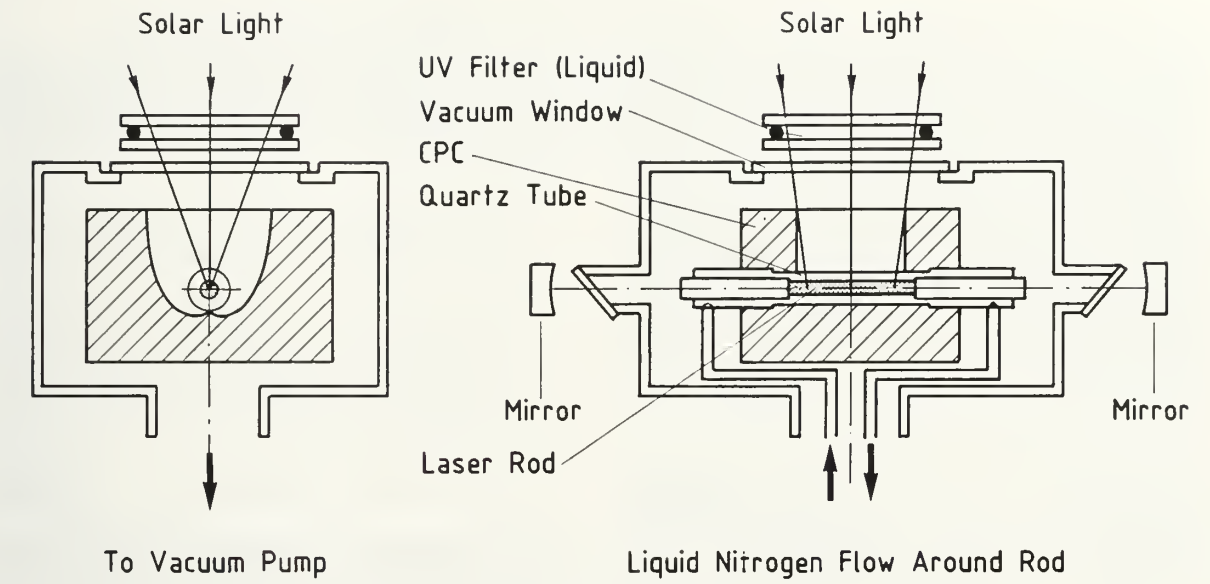

Figure 3: Laser head

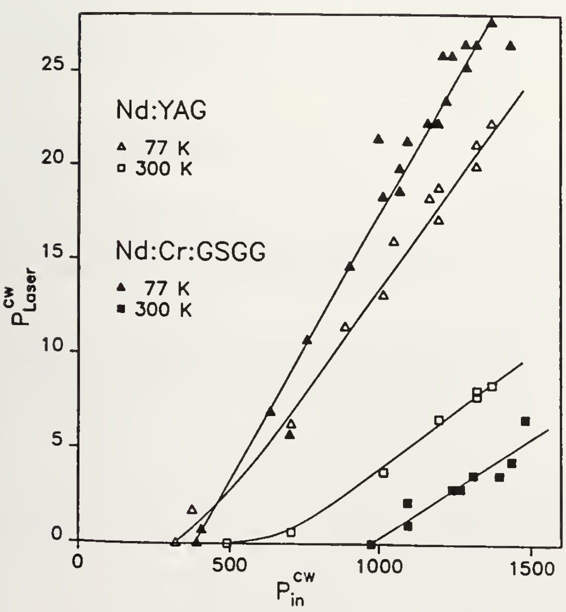

Figure 4: Laser power versus solar input power

cooling down to 77 K is not appropriate. The highest output power achieved in our experiment is 28 W corresponding to a solar into laser power conversion efficiency of 2.1% for the Nd:Cr:GSGG laser. The laser has a good beam quality (four times diffraction limited), but runs under unoptimized conditions, as mentioned earlier. So we can conclude that cooling indeed helps to increase the performance parameters of solar pumped solid state lasers.

V. Conclusion

We compared laser sources for space-space power transmission and found that direct solar pumped solid state lasers, especially the Nd:Cr:GSGG laser, are the best choice. Depending on the conditions, Nd:YAG lasers may also be useful. We have demonstrated, that the thermal problems, associated with high power CW solid state lasers, can be reduced dramatically by cooling. We have also shown that the overall system efficiency can be increased by splitting the solar spectrum into different parts for conversion to laser power and to electrical power. The estimated values are 17% for a laser/photovoltaic system and 27% for a laser/solardynamic system.

The results we achieved are encouraging. We therefore will concentrate our future work on the development of a 1 kW solid state laser to be excited in the

first experiments with a solar simulator and later on directly by the sun. In addition we will study the performance of the direct solar pumped solid state laser space-space power transmission system in more detail, including the cooling requirement.

We want to point out that a laser satellite for space-space power transmission may be a precursor for a space-earth energy supply system. In addition, a laser power satellite can also be used for laser thermal propulsion and laser debris removal. It is this potential multifunctional use of laser satellites which we think is very fascinating.

Acknowledgement

We thank A. Yogev and his group at the Weizmann Institute of Science, Rehovot, Israel, for the good collaboration in the experiments.

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SPS 91

A8.4 A lightweight focusing reflector concept for space power applications

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Abstract

Large diameter, lightweight reflectors have important applications in space power systems. In many of these applications, the ability to focus the reflected energy can be very useful. This work describes a novel lightweight reflector concept, consisting of a membrane supported at its circumference by an inflatable frame. The design allows adjusting the focal length by varying the circumferential tension.

Résumé

Les réflecteurs allégés de grand diamètre ont des applications importantes dans les systèmes spatiaux pour la transmission d'énergie. Il est utile, souvent, de pouvoir concentrer l'énergie réfléchie. Ce papier décrit une nouvelle conception des réflecteurs allégés. Cette conception consiste en une membrane supportée à la périphérie par une armature pneumatique, qui permet la variation de la distance focale par ajustage à la tension autour de la circonférence.

1. Introduction

Large reflectors have many important applications in space power systems. They may be used either to reflect sunlight onto a solar collector, or to redirect a microwave power beam. Often, it is beneficial to focus the reflected radiation onto the receiver. The design of the mirror is determined by the *f/D* ratio required by the application.

When the receiver is far from the reflector, high *f/D* reflectors are often required. Although high *f/D* reflectors cannot achieve the very high ratios of incident to focused power density of low *f/D* reflectors, they can often increase the power density by factors of 5-20. This improvement can be very important when the receiving system must be small.

This paper describes a very lightweight membrane mirror system which can function as a flat or concave mirror. The design also provides a simple means of altering the mirror focal length.

2. Construction

In its simplest form, the reflector consists of a thin membrane, supported at its edge by an inflatable frame. The membrane is initially flat, under tension applied around its circumference by the frame. When the incident radiation is applied, the radiation pressure stretches the membrane into a concave shape. The precise shape is determined by the elasticity of the membrane, the power density of the incident radiation, and the amount of circumferential tension applied.

The inflatable frame allows the tension to be varied in a very uniform manner by changing the pressure in the torus. In some circumstances, the need to stabilize the reflector orbit requires engines to be placed on the frame. A rigid outer structure may then be required in addition to the inflatable torus. (A discussion of the orbit stabilization system is given in Section 5.1.)

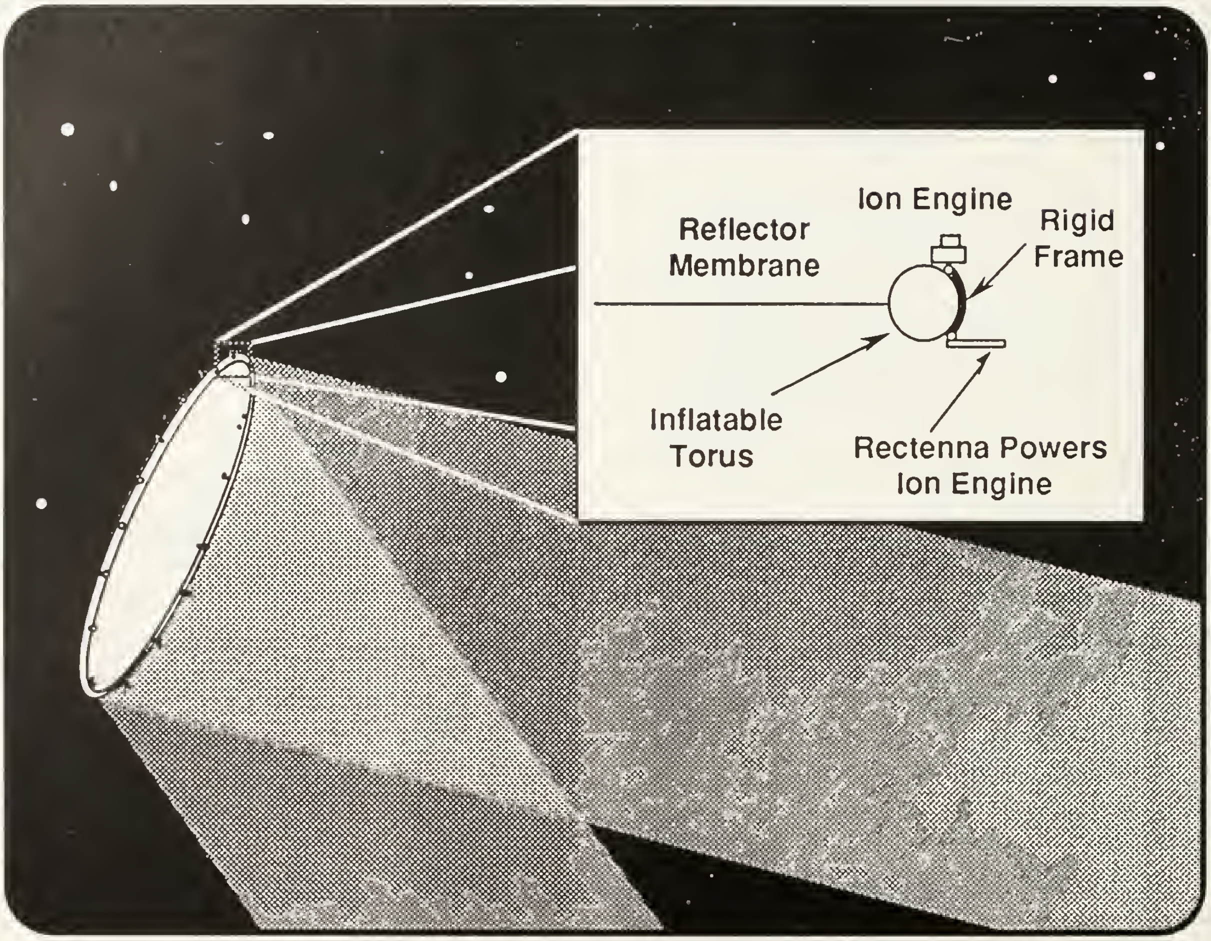

Figure 1. The Membrane Reflector Concept

3. Structural Properties

The mirror membrane shape is determined by the balance between the applied tension and the radiation pressure of the incident beam. An exact analysis of membrane shapes, stresses, and dynamic properties under varying conditions is quite complex, requiring the iterative numerical solution of several nonlinear differential equations. An outline of the exact steady-state solution method is given in Appendix A. For brevity, a simple case where the approximate shape and stress are easily determined will be described here.

3.1. Steady-State Design

If the incident radiation is uniform over the surface of the reflector, the pressure applied to the membrane is virtually uniform. When the proper tension is applied, the membrane experiences the same forces as a portion of the surface of a balloon with the same internal pressure.

The pressure experienced by the membrane is

$$P = \frac{(1+\rho)\ S}{c} \qquad (1)$$

where P is the pressure, ρ is the reflection coefficient, and S is the incident power density.

It is desired to approximate as closely as possible a spherical surface, where the stress in the membrane is uniform, and is given by

$$\sigma = \frac{P\ R}{2\ t} = \frac{(1+\rho)\ S\ R}{2\ c\ t} \qquad (2)$$

where R is the radius of curvature, and t is the thickness of the membrane. If the applied circumferential tension T is adjusted so that $T = \sigma\ t$, the membrane will be stretched into an almost exactly spherical shape. The radius of curvature is given by

$$R = \frac{2\ c\ T}{(1+\rho)\ S} \qquad (3)$$

The maximum power density is determined by the strength of the membrane material and the radius of curvature required. Because the membrane will be under tension throughout its lifetime, the operating stress in the membrane must be restricted to 10-20% of the yield stress by properly selecting the membrane thickness.

3.2. Dynamic Effects

A large stretched membrane has a considerable amount of stored energy. This energy is absorbed from the incident radiation when the beam is first applied, and released when the beam is shut off. Although the dynamic properties of membrane reflectors are of little importance for most solar concentrator applications, they must be taken into account in planning the operations of microwave power beaming systems.

The damping properties of inflatable structures are reasonably good, and may be further improved by the proper choice of materials and the use of active damping devices in the frame. Nevertheless, because of the very small surface tolerances required of millimeter-wave reflectors, it is expected that turn-on and turn-off transients may take as long as tens of minutes to decay to acceptable limits at these frequencies.

During the decay period, the elastic waves propagating across the surface of the mirror will cause sidelobe levels to far exceed those encountered in normal operation. At the high power densities expected of power beaming systems, these sidelobes may be unacceptable. In these cases, a gradual turn-on and turn-off procedure must be used to avoid exciting membrane resonances. This is not expected to interfere with the majority of applications.

4. Optical Properties

Employing the approximate analysis of Section 3, we find the membrane to have an spherical shape. For large f/D ratios, spherical mirrors perform nearly as well as an ideal paraboloidal reflector. In these cases, the mirror performance will be principally limited by diffraction and small-scale surface irregularities.

The focal length of a spherical mirror is half of the radius of curvature. From (3) we find the relationship between focal length and applied power density to be

$$f = \frac{2\,c\,T}{(1+\rho)\,S} \tag{4}$$

The minimum focal spot diameter is

$$D_{spot} \approx \frac{\lambda f}{D} \tag{5}$$

Extremely high f/D ratios produce results indistinguishable from a flat mirror. The increase in power density at the receiver is

$$\frac{S}{S_0} = \frac{\lambda^2 f^2}{D^4} \tag{6}$$

for a source at infinity.

5. Operational Issues

During the preliminary analysis of the mirror concept, several issues affecting the operation of the reflector system were examined. Some of these issues require slight modifications to the design or the operating procedure in certain circumstances. Each of these issues is briefly discussed below.

5.1. Orbit Stabilization

When the reflector must be maintained in a stable orbit , it is necessary to apply a force of

$$F = \frac{(1+\rho)\,P}{c} \tag{7}$$

to counteract the radiation pressure of the reflected power beam. This may be accomplished by using high specific impulse engines mounted on the frame, which draw power from the edges of the RF beam or from solar arrays.

Electric engines, particularly ion engines, are well suited for this application. If the reflector is used in a microwave power beaming system, a small fraction of the beam incident on the edge of the frame may be converted to power for the engines. If the reflector is used as a solar concentrator, the power must be supplied by solar cells. The power required is

$$Q_{eng} = \frac{(1+\rho)\,Q\,g I_{sp}}{2\,\varepsilon\,c} \tag{8}$$

where ε is the overall efficiency of the engine, including the power supply, I_{sp} is the specific impulse, and Q is the total reflected power. The

ratio of the reflected power to the power required for orbit stabilization is

$$\frac{Q_{eng}}{Q} = \frac{(1+\rho)\, g I_{sp}}{2\,\varepsilon\, c} \approx 3.3 \times 10^{-5} \frac{I_{sp}}{\varepsilon} \qquad (9)$$

This sets a lower limit for the practical size of the system as a function of the engine design and the system capacity.

The required propellant mass is given by

$$M_{prop} = \frac{(1+\rho)\, Q}{c\, g I_{sp}}\; L \qquad (10)$$

where L is the lifetime of the system. The power requirement and the propellant mass must be traded off; for RF power systems, where a large amount of electric power is readily available from rectennas on the frame, high I_{sp} engines are optimal.

5.2. Deformation by Solar Pressure

In microwave power beaming applications, if the incident power density is less than several tens of kilowatts per square meter, a noticeable deformation of the reflector surface may be caused by solar radiation pressure. If precise focal control is necessary, the incident power density or the circumferential tension may be adjusted to compensate.

If this is impractical, it would also be possible to add outer reflectors to the front and back of the frame. These membranes with very thin aluminization would reflect the majority of the incident solar radiation, while remaining almost completely transparent to the microwave beam.

5.3. Pointing Control

Virtually all power beaming systems envision the use of a fail-safe device which shuts down the transmitter if the power at the receiver falls, either because of a beam pointing error or a blockage between the transmitter and receiver.

At geosynchronous distances, the delay of a fail-safe system will be less than 0.5 seconds. Even the maximum pointing error which could occur during this period because of a worst-case failure of the orbital stabilization engines is unlikely to cause pointing errors of more than a few beam diameters.

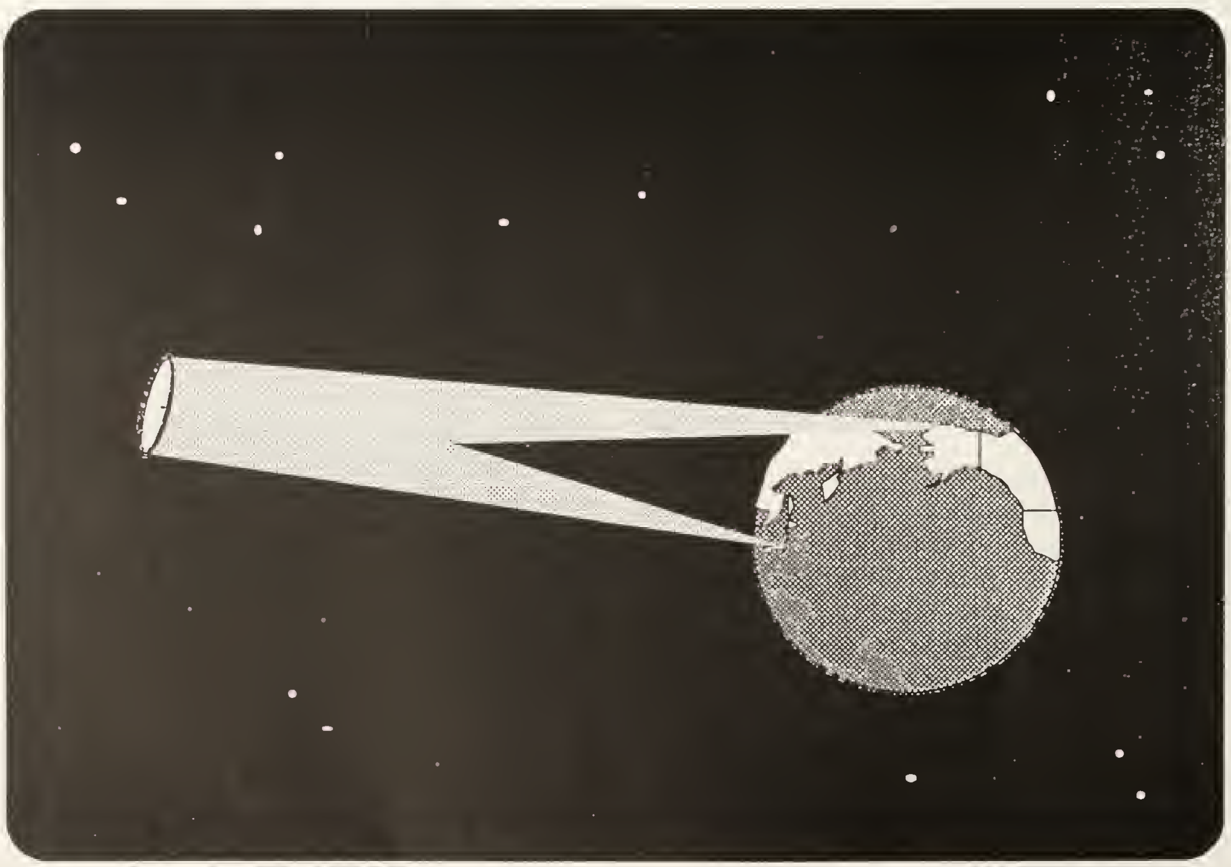

Figure 2. An Example Application

6. An Example System

The membrane reflector was originally conceived for use in a 35 GHz power relay system for use between terrestrial power stations and customers separated by distances of several thousand kilometers or more. In this example, a transmitter of 2 kilometers diameter and a receiver of 2 kilometers diameter employ a reflector 500 meters in diameter in geosynchronous orbit, as shown in Figure 2.

The orbiting mirror must focus the reflected energy on the receiving station 45 000 km. away, so the radius of curvature required is 90 000 km. The system transmits 10 GW of power, which results in a power density at the membrane of 51 kW/m^2.

The membrane is assumed to be made of kevlar-reinforced mylar film, which has a maximum working strength of 690 MPa (100 ksi). The material is assumed to be aluminized on the reflecting side to five skin depths, or 2 μm, giving a reflectivity of 99%. The membrane is also slightly aluminized on the back to reduce UV embrittlement during the system's lifetime.

The membrane stress will be set at 20% of the maximum working strength, or 138 MPa. From (2), the required thickness is 0.11 mm. The membrane mass per unit area is 0.16 kg/m2, and the total mass of the membrane is 32 tonnes. The supporting torus is made of the same material in 0.5 mm thickness, and is 10 m in diameter, adding 36 tonnes to the reflector mass.

The other major contributor to the system mass is the propulsion system and its propellant. One hundred advanced ion engines, each with a thrust of 0.7 N, a mass of 20 kg (including power supply), and an I_{sp} of 35 000 are mounted on a rigid composite plate attached to the back of the torus. Each engine requires 100 kW of electric power, which is provided by individual 5 m^2 rectennas mounted on the edge of the torus. The total weight of the engines, mountings, and the rectennas is 5 tonnes.

For a 10 year lifetime, the system will require 61 tonnes of propellant. This is stored in individual tanks at each engine, and a tankage fraction of 0.2 is assumed. This brings the total propulsion system mass to 78 tonnes.

The total system mass is 146 tonnes, which compares favorably to inflatable antennas and is far better than rigid alternatives.

Appendix A. Membrane Equations

The equations of equilibrium for an element of a surface of revolution under the action of a symmetrical pressure P and tensions T_r and T_φ are

$$\frac{d}{dz}(r T_r) - r' T_\varphi = 0 \qquad (A.1)$$

$$-r r'' \frac{T_r}{1 + r'^2} + T_\varphi - r\left(1 + r'^2\right)^{1/2} P = 0 \qquad (A.2)$$

The displacements u and w of an elastic membrane, in the radial and normal directions respectively, are given by

$$\begin{aligned}\frac{du}{d\alpha} - u \cot\alpha &= \left(R_r + \nu R_\varphi\right)\frac{T_r}{E} \\ &\quad - \left(R_\varphi + \nu R_r\right)\frac{T_\varphi}{E}\end{aligned} \qquad (A.3)$$

$$w = -R_r\left(\frac{T_r - \nu T_\varphi}{E}\right) + \frac{du}{d\alpha} \qquad (A.4)$$

where E is Young's modulus, ν is Poisson's ratio, R_r and R_φ are the radii of curvature along the coordinate directions, and α is the angle between the surface normal and the rotational axis.

This set of equations must be solved iteratively, starting with an assumed shape, and proceeding until (A.3-4) show zero displacements, indicating that the surface is in equilibrium.

An examination of the effects of nonuniform illumination on the membrane shape, using the technique described above, is currently in progress, and will be reported upon at a later date.

A8.5 The application of electric propulsion to powersat demonstrators

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1 INTRODUCTION :

The POWERSAT concept is characterized by a much larger specific power than conventional spacecrafts. This offers new perspectives in the use of electric propulsion. However, the electric propulsion cannot be introduced in any phase of the mission, especially during the end of injection. The first part of the paper is devoted to the identification of the various propulsion needs during the whole mission and their requirements. Then the expected benefits of electric propulsion are illustrated, especially in terms of mass flow from earth.

Several technologies (ion, arc jet, MPD, resistojet) could be used. Each technology presents an advantage for a given application. The conclusion illustrates that there is no universal solution and that new developments are necessary to fully optimize electric propulsion thrusters for this new use.

2 PROPULSION REQUIREMENTS :

From the end of launcher burning (slighly suborbital in the future to avoid LEO debris build up) the following mission steps shall be performed :

In the case of LEO missions
(the most probable application for near term missions) :
- orbit transfer (suborbital to LEO),
- attitude acquisition,
- attitude control,
- drag compensation.

In the case of near GEO missions
- orbit transfer,
- attitude acquisition,
- attitude control,
- inclination control (lunisolar perturbations), also called NSSK (North South Station Keeping)
- longitude control (earth potential and solar radiation pressure), also called EWSK (East West Station Keeping) .

LEO missions :

The order of magnitude of Delta V is given in the table 2.1 for LEO missions (except drag compensation). In addition, the figure 2.1 gives the Delta V needed for drag compensation versus altitude, ballistic coefficient and atmosphere density.

This last figure shows that the drag is very sensitive to the atmosphere density i.e. the solar activity. Therefore, the drag compensation system shall be built with a very large margin of safety and will be understessed most of the time.

When chemical thrusters are used for this function, they induce attitude disturbances forbidding any fine pointing. Some electric thrusters can be used to cancel the drag in a proportional mode zeroing the signal of a microaccelerometer.

Fine attitude control :

The fine attitude control is a prerequisite for beamed energy transmission in space, especially if the energy is transmitted by lasers ; this fine control is generally directly effected by reaction wheels. These wheels need to be desaturated frequently, sometimes at each orbit. This can be performed by magnetotorquers (this is the case of SPOT spacecraft) but the POWERSAT payload may forbid the use of magnetotorquers if it generates itself very strong magnetic fields (superconducting magnets). Worse, the torque impressed by the interaction of earth and spacecraft fields may need themselves to be cancelled. Since the wheels need to be very gently desaturated, a low thrust device shall be used for this function when magnetotorquers are not suitable or used as a backup to correct wheels and / or magnetotorquers failure.

Table 2.1

Delta V LEO requirements

Orbit : circularization	100 to 300 m/s
Attitude control :	2 to 10 m/s per year
Orbit maintenance :	2 to 10 m/s per year (excluding drag compensation)

Near GEO missions :

The order of magnitude of Delta V is given on table 2.2 for near GEO missions. The term "near "GEO means that, due to the restricted availability of geostationary orbit slots, it may be necessary to use a slightly different orbit.

The highest contribution is the LEO to GEO transfer. For some launchers (ARIANE) the transfer is directly performed in GTO. The use of electric propulsion allows for a spiralling transfer at the expense of a fairly slow crossing of Van Allen belts. To avoid this, electric propulsion can only be used for the last part of the transfer.

The other function of electric propulsion is the NSSK mission which requires a V of 500 m/s for in geosynchronous orbit 10 years. If a very large structure is used (low K), the solar radiation pressure induces sizable disturbances which affect the East West positioning ; it is therefore interesting to use electric propulsion for EWSK.

Fine attitude control :

As for LEO applications, the fine attitude control is a prerequisite for beamed energy transmission, this fine control is generally directly obtained with reaction wheels. The wheels desaturation obeys to the same constraints than in LEO, except that the orbital period is longer.

Table 2.2
Delta V GEO requirements

LEO /GEO transfer	
Hohmann :	4500 m/s
Spiralling :	6000 m/s (depends on trajectory)
Orbit control :	
NSSK :	50 m/s per year
EWSK : Ballistic coefficient (K)impact :	
K> 10 kg/m^2 :	2 to 5 m/s per year
K< 100 g/m^2 :	20 to 50 m/s per year (effect of solar radiation pressure)
Attitude control :	2 to 5 m/s per year

3 E.P. EXPECTED BENEFITS :

The electric propulsion offers two main advantages :

* the specific impulse is higher than the one of chemical thrusters,
* the thrust being generally small, the attitude disturbances and flexible structures excitation are reduced drastically.

The higher the specific impulse is, the lower the propellant mass to be transferred from earth for orbit and attitude control. If the mass is sufficiently small, the POWERSAT can be launched with its propellant reserve for the whole mission.

LEO drag compensation :

This advantage can be extended to the payloads serviced by the POWERSAT, like the Space Station. One of the largest earth to orbit mass flux contribution is the propellant needed for drag compensation. The direct introduction of electric propulsion on the Space Station or MTFF has been looked for, but these studies show that the solar panels surface must be extended to deliver the required power, this in turn increases the drag. Since the specific power increases with specific impulse, it exists a specific impulse upper limit where the solar panel increase is indefinite. There is no such limit with the POWERSAT concept since it can be located on an higher orbit with far lower drag.

4 PROPULSION TECHNIQUES :

Four types of electric thrusters are good candidates for the mission :
- ion thrusters,
- arc jets,
- continuous MPD,
- resistojets (especially biowaste resistojet)

Their respective performances are shown on figure 4.1.

Ion thrusters :

The ion thrusters (bombardment or radiofrequency) present a very high electrical efficiency (70 to 90 %), a high specific impulse, a long life potential (> 10000 h) and very smooth operation (thrust throttling capability). On the other hand, they present a fairly high specific power (20 to 40 W/mN), a low thrust density (1 to 3 N/m^2) and they need rare gas (Krypton or Xenon) or Cesium or Mercury as propellants as well as an elaborated power supply.

The problem of Xenon availability may be a limitation beyond 1 ton of Xenon (primary propulsion missions).

The state of the art offers thrust range from 5 mN to 500 mN at a very high level of development (qualification testing).

This thrust level is sufficient for most secondary propulsion missions and for primary propulsion missions involving masses lower than 15000 kg. For larger payloads, new kinds of ion thrusters should be developped.

Arc jets :

The arc jets use the gas ionization by an electrical discharge at medium pressure (0.5 to 10 bar). A low molecular mass gas shall be preferably used. Ammonia, hydrazine are good candidates. Hydrogen gives higher specific impulse but liquid hydrogen storage is a very difficult problem especially for long duration.

Despite some problems, such as limited lifetime (1000 h) and relatively low efficiency (25 to 40 %), which can be improved either by using new materials (ceramic and composite for wear resistance) or new geometry for efficiency, there is everywhere an increasing interest for arcjets due to :

- their simplicity and then an expected high reliability,
- the high available current density,
- the good specific impulses ranging from 500 s for low power arcjet (1 kW) to about 1000 s foı higher power (30 kW).

Arc jets are developped for space use with power levels of 1.2 to 30 kW. There is no anticipated difficulty to develop higher power models. Ground facilities offer power levels in excess of 5 MW.

Continuous MPD :

The continuous MPD is interesting only for power levels beyond 100 kW ; it can operate with a large number of propellants including argon. The plasma acceleration is generally obtained by the magnetic field generated by the discharge (self field MPD), although some models use an external solenoid.

Due to the lack of foreseenable power source, the MPD have been less developped than arcjets.

Their efficiency is fairly low (15 to 35 %), but tend to increase with power level. The specific impulse depends on the propellant, but values between 1000 and 3000 s have been recorded.

Resistojets :

The resistojets are intesting in two cases : hydrogen resistojet and biowaste resistojet (water and carbon dioxide or methane).

Hydrazine resistojets, which are used on telecommunication spacecrafts, are not considered for the intended use, as they are surpassed by the hydrazine arc jets.

The hydrogen resistojet offers the advantage of a good electrical efficiency (50 to 75 %) and reasonably high specific impulse
(800 s).

The biowaste resistojet makes sense only if it is used onboard a manned station. Its specific impulse is moderate (160 to 200 s), but it uses only products which shall be anyway eliminated : excess water, CO_2 or (much better) methane from the conversion of CO_2 by hydrogen in a Sabatier reactor. In that case, there is no supplementary mass flux penalty from earth.

5 OPTIMUM SOLUTIONS :

Near term, LEO missions :

Since in most cases, the payload power will not be available just after launch, the orbit circularization shall be performed by chemical propulsion.

The attitude control shall be performed preferentially by ion thrusters.

Ion thrusters are also a very good solution for spacecrafts orbiting beyond 500 km altitude and reasonable ballistic coefficients.

At lower altitude, arc jet is the best solution for automatic platforms in order to counter high atmospheric density periods. Hydrazine propellant could be a good choice.

Medium term, GEO missions :

For heavy spacecrafts, the acquisition of a LEO orbit is the first step to be performed by chemical propulsion. The question wether or not spiralling transfer (using electric propulsion) shall be used is still open due to the risk of irradiation in the Van Allen belts. The studies already performed show that it is not paying off to perform the initial raise with high Isp systems. Two solutions remain : chemical transfer up to a given altitude and then primary ion propulsion, arc jet for one third of the mission, ion thruster for the remaining.

6 CONCLUSION :

The POWERSAT concept will certainly increase the interest for the higher performances given by the EP compared to classical chemical propulsion system. This paper intended to clearly demonstrate that in electric propulsion several systems are actually developped and that their performances are in general well suited to a given type of mission.

Arcjets and ion thrusters appear as the more suitable propulsion system for to day or near future, ion thruster for low thrust application (NSSK, drag compensation, ...) whereas arcjets are more convenient for primary propulsion missions (orbit raising or drag compensation of large structures in low orbit).

The main development effort in Europe and U.S.A. deals with these two EP systems and first operational demonstrations are being prepared (ARTEMIS).

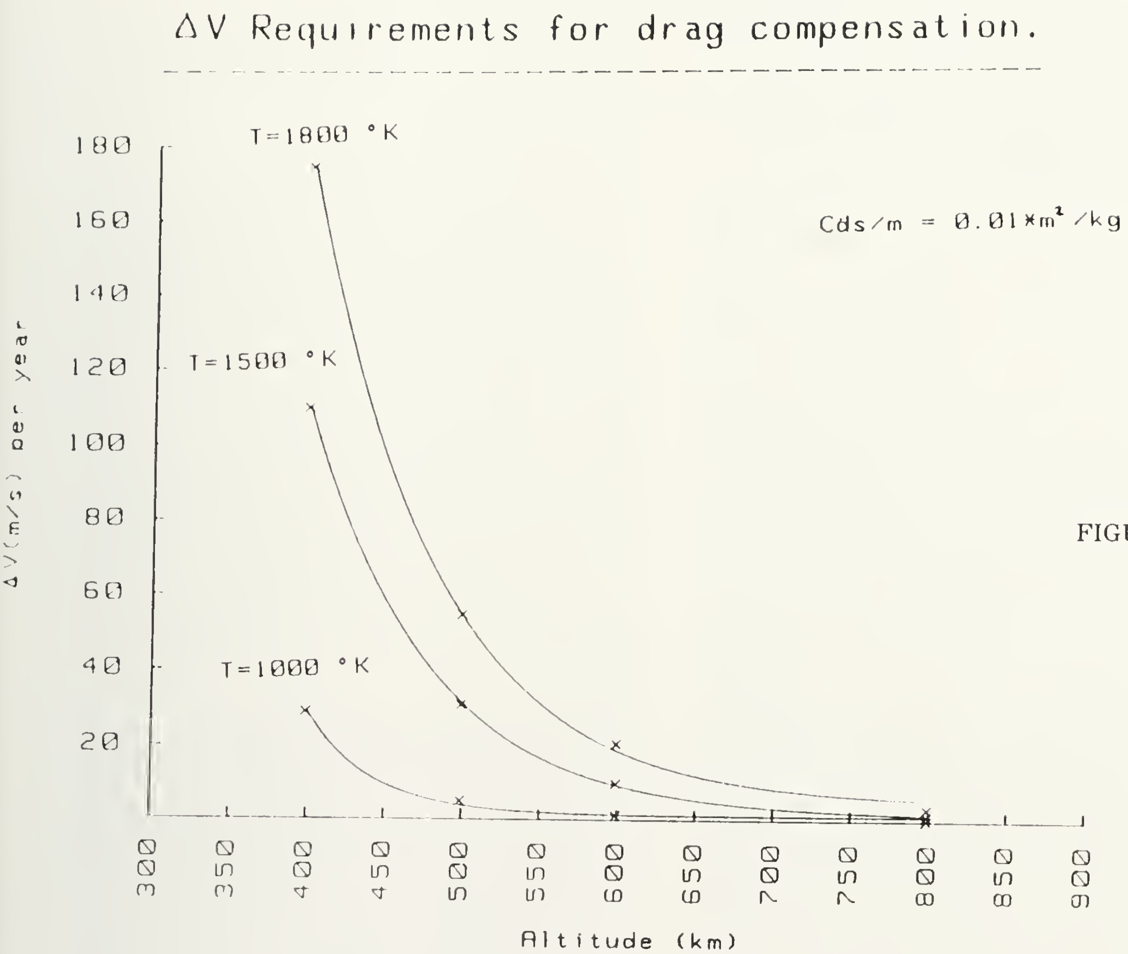

FIGURE 2.1

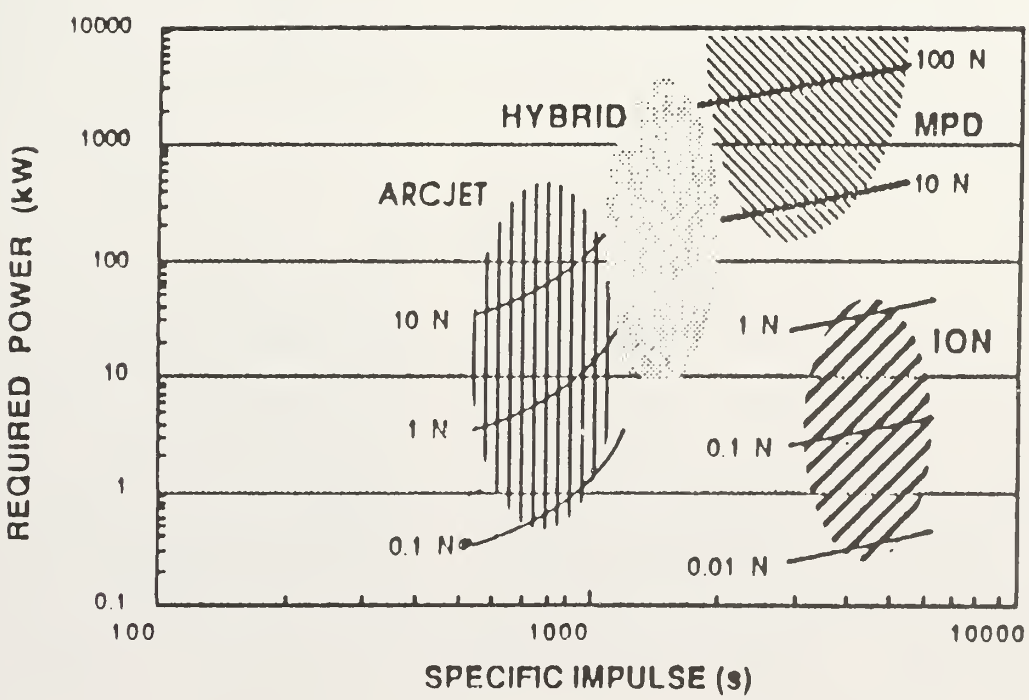

FIGURE 4.1

Performance ranges of electric propulsion systems

B1.1 Rocket experiment METS - Microwave Energy Transmission in Space

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Abstract

A METS (Microwave Energy Transmisson in Space) rocket experiment is being planned by the SPS (Solar Power Satellite) Working Group at the Institute of Space and Astronautical Science (ISAS) in Japan for the forthcoming International Space Year (ISY), 1992. The METS experiment is an advanced version of our previous MINIX rocket experiment[1-7]. In this paper, we describe a conceptual design of the METS rocket experiment.It aims at verifying a newly developed microwave energy transmission system for space use and to study nonlinear effects of the microwave energy beam in the space plasma environment. A high power microwave of 936 W will be transmitted by the new phased-array antenna from a mother rocket to a separated target (daughter rocket) through the ionospheric plasma. The active phased-array system has a capability of focusing the microwave energy around any spatial point by controlling the digital phase shifters individually.

Résumé

L'experience fusée METS (Microwave Energy Transmission in Space) est planifiée pour la prochaine Année Internationale de l'Espace (ISY) en 1992 par le groupe SPS de l'Intitute of Space and Astronautical Science (ISAS) au Japon. L'experience METS est une version avancée de notre précédente experience fusée MINIX [1-7]. Dans cet article, nous décrivons la conception de l'experience METS. Elle vise a tester un nouveau système d'émission d'énergie micro-onde à usage spatial, ainsi qu'à étudier les effets non linéaires du faisceau d'énergie micro-onde dans le milieu du plasma spatial. Un faisceau micro-onde de grande puissance, 936 W, sera émis par un ensemble d'antennes à phase contrôlée, d'une fusée mère vers une cible séparée (la fusée fille) à travers le plasma ionosphérique. Le système actif de l'ensemble des antennes a la capacité de concentrer l'energie micro-onde autour d'un point de l'espace en contrôlant individuellement chaque decaleur de phase digital.

1 Introduction

The Solar Power Satellite (SPS), which was first proposed by Dr. Peter E. Glaser[8], is a very unique and hopeful power supply to ever-increasing energy demand on the earth without destroying the environment of our mother planet. Our goal is, however, not only to construct such SPS for use of power suppliers to the earth, but also to establish a technology of power suppliers to long-scale space structures such as Space Stations, Space Factories and Space Cities. They will demand much larger amount of electric power, possibly without having a large and heavy structure of solar cells. If we could supply electric power by wireless transmission to them, they will be able to capture the electricity through simple and lightweight rectennas. Therefore we need to develop an effective energy transmission system with a capability of high speed and accurate beaming of microwave energy toward the target consumers, some of which may move fast in their orbit. We have developed a microwave energy transmitter for a rocket experiment, called METS (Microwave Energy Transmission in Space), hiring a semicondutor power amplifier connected to arrays of antennas. A research group (Chief: Prof. H.Matsumoto) was organized in the SPS Working Group (Chairman: Prof. K.Miura) at ISAS to promote the METS rocket experiment. We describe our concetptual design of the METS in this paper.

2 Development of FET Microwave Transmitter

We have developed a microwave transmission system which uses a phased-array antenna connected directly to a power amplifier and a digital phase shifter. The power amplifiers are of the F-class type GaAs-FET semiconductor. More than 50 % efficiency of the amplifier has already been achieved.

To facilitate a capability of the beam control without any phase ambiguity, a new two-tone pilot signal system has been developed. The retrodirective antenna system[9] seems to be the most effective technique to accurately point a microwave beam to a receiving site. To overcome the well-known drawback of the conventional retrodirective antenna, we have developed a new two-tone pilot signal system which can determine the phases of the transmitting microwave with no phase ambiguity. A brief block diagram of the two-tone pilot signal system is shown in Fig.1.

Figure 2 shows the pointing errors of the transmitting microwave determined by the two-tone system. They stay below one degree on the average of seven phase conjugate circuits, while the error by a single pilot system increases with increasing path difference.

In addition to the retrodirective antenna, we have developed a computer control system. The computer system can flexibly determine the phases of the transmitted microwave by controlling digital phase shifters. To control the phase sifters, we have developed a neural network control system. The neural net-

work is used to find out malfunctioning antenna elements from a huge number of array elements.

A prototype of a microwave transmitter sub-array shown in Fig.3 has been developed with the capability of the retrodirective phase control. Seven dipole antennas are mounted on a flat hexagonal plate, which has a diameter of about 20 cm and a height of about 30 cm. Phases of the transmitted microwave are initially determined by a phase conjugate circuit by receiving two-tone pilot signals. The signal is distributed to seven digital phase shifters, each of which is connected to the dipole antenna through a F-class power amplifier. The phases of the microwave transmitted from the antennas can be individually modified by the phase shifters so that it has a capability of focusing and pointing the microwave. This subarray system can generate 2.45 GHz microwaves with an output of 90 Watts.

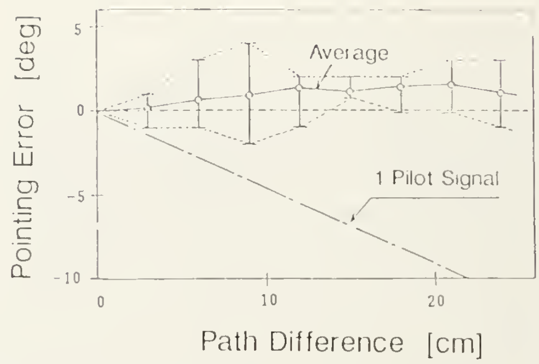

Fig. 2 Pointing errors of the transmitting microwave in the two-tone and the single pilot systems.

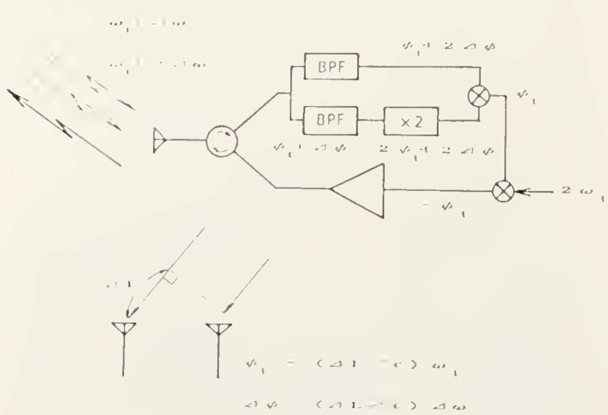

Fig. 1 Block diagram of the two-tone system.

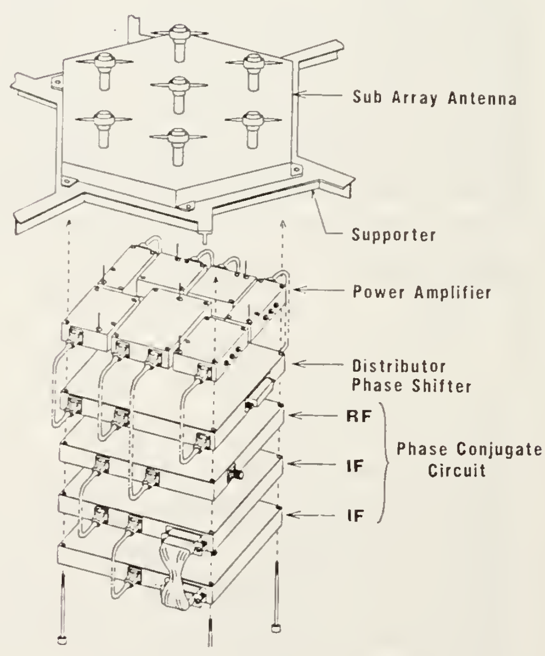

Fig. 3 Configuration of the newly developed sub-array of the microwave transmitter.

3 Concept of METS Rocket Experiment

3.1 Objectives

The METS rocket experiment has two objectives. One is an in situ demonstration of the microwave energy transmission to verify a technological capability of the newly developed phased-array system in space circumstances. The microwave energy transmission test using the computer control system will be conducted toward a target daughter rocket. An attempt of energy concentration on one point in space will also be made using the steerability of the beam by computer controlled phase shifters. We will also perform a ground-based energy transmission test of the developed system by using a small model airplane as a target before the launch. The airplane will fly around at a height of about 15 m only by the recieved microwave energy. The space and ground tests will provide a good opportunity of demonstrating a feasibility of the wireless energy transmission in addition to critical technical data of the system.

The other objective is to study nonlinear plasma effects of the high power microwave energy beam in the space environment. If the intensity of the microwave is of the order of that used in the communication, very little effect to the ionospheric plasma would be expected. However, the power density of the microwave for the power transmission is twelve orders of magnitude higher than that for communication use. Therefore, strong nonlinear effects are expected such as plasma heating and nonlinear scattering which cause the excitation of various plasma waves. The METS rocket experiment provides a unique oppotunity of an advanced scientific research on this subject.

3.2 Configuration of the Payload Section

The METS plans to use a mother-daughter rocket. The mother section is mainly used for the microwave high-power transmission, while the daughter section carries a microwave receiver and diagnostic packages to detect plasma responses. The conceptual configuration of the METS rocket is shown in Fig. 4.

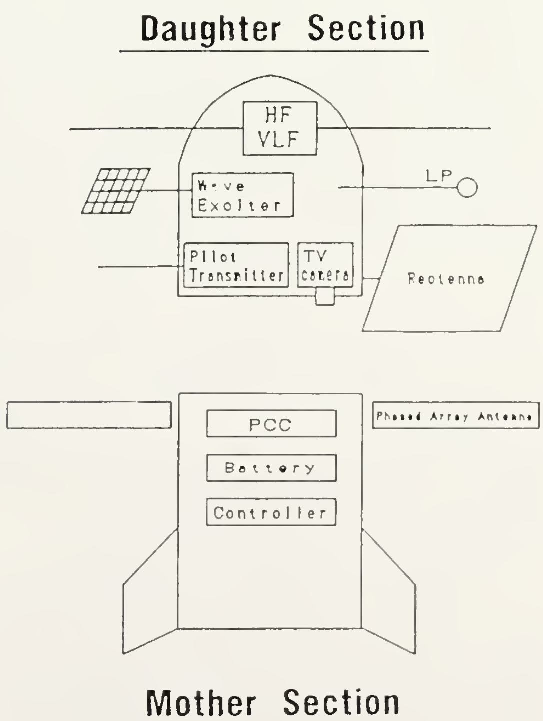

Fig. 4 Conceptual configuration of the METS rocket.

3.2.1 Microwave Transmission System

The new transmitter system will be used to radiate a stable and purely monochromatic microwave of 2.45 GHz. The transmitting antenna consists of four antenna paddles, each mounting 18 microstrip antennas. The antenna paddles are deployed in a cross shape on the top of the mother section. The transmitting power and the gain of the phased array antenna will be 936 W and 26 dB, respectively. Figure 5 shows a calculated radiation pattern of the transmitter antenna. Though it has large side-lobes, we can find a region of power concentration with an elongated oval shape. The antenna paddle has a sandwich structure of three layers; the microstrip antennas, ground and FET amplifilers as shown in Fig. 6.

Only the computer system with a 4-bit digital phase shifters is used as the microwave beam control for the METS. The reason is that the computer control system can adequately change both of the power density and the direction of the microwave for technical and scientific purposes, while the retrodirective antenna can focuss the microwave only to the pilot signal transmitter.

Two optical position sensitive detectors will be installed to measure relative distance and direction between the mother and daughter rockets. The computer determines the most suitable direction of the microwave beam from the data of the position sensitive detectors and geomagnetic field detectors.

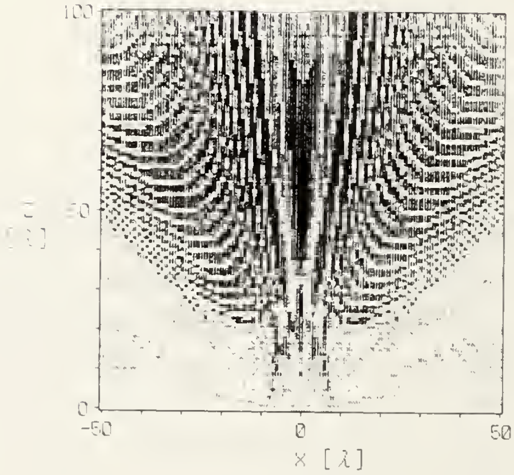

Fig. 5 Calculated antenna pattern of the phased array antenna installed on the METS rocket.

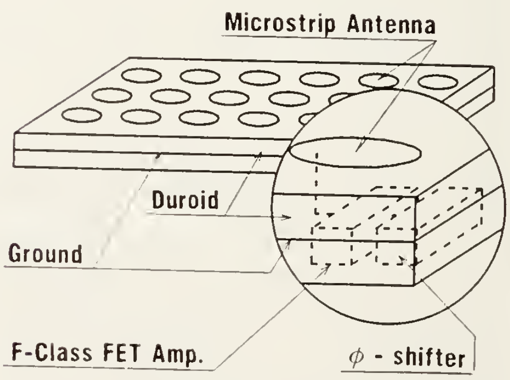

Fig. 6 Structure of the antenna paddle.

3.2.2 Diagnostic Package

The diagnostic package consists of four scientific instruments to observe plasma phenomena excited by the high power microwave. In order to reveal nonlinear interactions between the high power microwave and the ionospheric plasma, they measure parameters of plasma (electron density and temperature) and plasma waves in a wide range

from VLF to HF. The antennas of the HF, VLF and Impedance probe will be deployed on the top of the daughter section.

3.3 Experimental Operations

The experimental schedule is divided into three experimental phases (see Fig. 7). All the antennas for plasma observation and microwave receiver except the microwave antenna paddles will be deployed soon after a nose cone covering the instrument is released from the rocket at 60 sec after launch. The first phase will be spent for engineering check of the microwave transmitter. The paddles folded in the payload section will radiate microwave for an initial test. The paddles will then be deployed after the test so that the second phase of the experiment will begin to examine the nonlinear plasma wave excitations in the natural ionosphere. The daughter rocket will be connected with the mother section during the second phase.

The daughter rocket carrying the diagnostic package will be separated in the last phase by very weak springs as slowly as possible from the mother, desirably below 5 cm/sec, because the effective area for the experiment with the intense microwave field is very limited only in the vicinity of the transmitter. Many kinds of the transmission modes are planned in the third phase. The direction of the microwave beam will be controlled toward the microwave receiver onboard the daughter for the energy transmission demonstration. While the microwave energy will be concentrated into one point near the daughter rocket to effectively observe the nonlinear plasma instabilities.

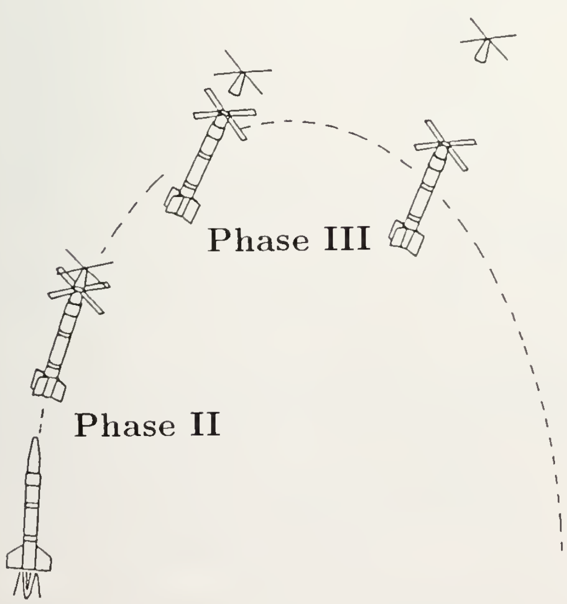

Fig. 7 Time schedule of the METS rocket experiment

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B1.2 Demonstration of microwave power transmission in space

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Abstract
Three separate experiments aboard the space shuttle are proposed to demonstrate the feasibility of microwave power transmission in space. This paper describes those proposed experiments.

Résumé
Trois expériences distinctes à réaliser à bord du Shuttle ont été proposées pour démontrer la faisabilité de la transmission de puissance par microondes dans l'espace. Cet article décrit ces expériences.

I. Introduction

Efficient power transmission using microwave beam in free space provides a potential energy generation and delivery system for many space applications [1-4]. The availability of power for use in space is a key issue for future space activities. At present, most satellites and space vehicles carry their own solar panels, batteries, fuel, and related equipment. These methods of power generation and storage are disadvantageous because of their heavy weights and difficulties in packaging the power system, unfolding the system in space, orienting the system toward the sun, and achieving high output power. Power becomes a limiting factor in many future space missions. To overcome these problems, DC power could be converted into microwave or millimeter-wave beam and transmitted to users through free space. The generator could be located on earth or on a utility power satellite (i.e. a space power plant). The received power would then be converted back into DC or AC power.

Three experiments are proposed to demonstrate the feasibility of this approach. The Phase I experiment will be conducted in 1993, and 2.45 GHz microwave power transmission will be demonstrated on the shuttle bay. Power transmission at 2.45 GHz from the shuttle bay to a remote target will be demonstrated in the Phase II experiment. In the Phase III experiment, the power transmission will be conducted at 35 GHz from the shuttle to a remote target.

In the first experiment, the microwave power will be transmitted from a reflector antenna located on the shuttle bay and collected by a rectenna attached to the remote manipulator system (RMS). The transmission distance will be varied from 10 to 20 meters during the experiment. The transmitted RF power will be 250 W and the DC power out of the rectenna will be 150 W with an RF to DC conversion efficiency of 60 percent. A magnetron will be used as the RF generator and a 8-ft reflector antenna will be mounted on top of a Hitchhiker M carrier.

(For explanation please refer to top of p4. of this paper).

The Phase I experiment will pave the way for the Phase II and III experiments. The Phase II and III experiments will be designed to transmit the microwave / millimeter-wave power from the shuttle bay to a remote free - flying platform at a distance of less than 1 Km at 2.45 and 35 GHz, respectively. The success of these experiments will demonstrate the feasibility of microwave power transmission in space and eventually lead to the commercial use of this technology.

II. Phase I Flight Experiment

The Phase I flight experiment will use a 2.45 GHz system transmitting over a relatively short distance (about 20 meters), from a microwave transmitter in the Space Shuttle payload bay to a rectenna attached to the end of the Remote Manipulator System (RMS) as shown in Figure 1. This

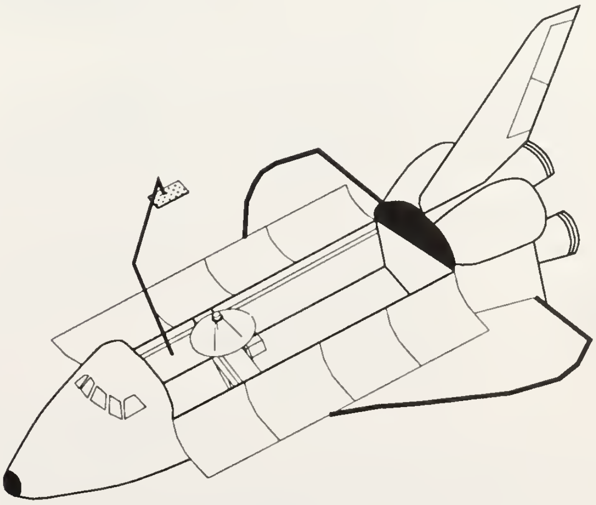

Figure 1
Schematic diagram showing the experimental arrangement

approach represents one of low risk, maximizes the use of existing components, and requires minimum complexity in Space Shuttle integration and in-flight activity. Despite its simplicity, this experiment represents the first known United States space demonstration of this promising technology. Table 1 summarizes the major specifications for this experiment.

The experiment will obtain necessary engineering data on microwave hardware operating in space: validate ground-based design methods; and provide system data for the design and economic analyses of future commercial systems.

- Frequency : 2.45 GHz
- RF power output : 250 W
- DC power output : 150 W
- Transmission distance : 10 to 20 m (From shuttle bay to RMS)
- Transmitting antenna size : 8 ft (2.44m) dish antenna
- Receiving rectenna size 2 m x 2 m
- RF generator : magnetron
- Required DC power : 1.2 KW
- Experiment duration : 30 minutes
- Efficiency (RF to DC) : 30 to 50%

Table 1
Summary of specifications for Phase I experiment

Components:
A microwave frequency of 2.45 GHz was selected for the Phase I flight experiment so that currently available, off-the-shelf hardware (i.e., magnetron, transmitting antenna, rectenna) could be utilized. The frequency is within the ISM band reserved for industrial, scientific and medical use; microwave ovens and microwave industrial processing equipment fall within this band. Microwave technology at higher frequencies (i.e., 35 and 94 GHz) is just now being developed by several companies and laboratories [5].

A microwave oven magnetron is being reconfigured for use as the microwave generator for the flight experiment [6]; an anodized aluminum fin is being added to radiate thermal energy from the magnetron directly to space. The magnetron is a low-cost, readily-available item used in microwave ovens, and has the following characteristics:

- 2.45 to 2.47 GHz frequency of operation;
- 3.4 to 3.7 kV, 150 mA DC input power;
- 250 W RF output power;
- 60% nominal efficiency;
- 2.4 kg mass; and
- 10 inches diameter and 6 inches long.

A parabolic antenna will be used to broadcast a microwave beam. The beam will illuminate a thin-film rectenna attached to the end of the RMS. The transmitting antenna will be mounted upon a Hitchhiker-M carrier near the forward end of the Space Shuttle payload bay. The RMS will position the rectenna at about 20 meters from the transmitting antenna. The transmitting antenna is characterized as follows:

- 8 foot diameter;
- 88 kg mass;
- 2.45 GHz frequency;
- 4.5 degree beam width;
- 31 dB gain;
- VSWR: 1.5 max.;
- -18 dB sidelobe; and
- 10 kW power handling.

The rectenna (rectifier antenna) converts the microwave power into DC power. The 2.45 GHz rectenna has been developed using thin-film technology with an efficiency of over 85% [4,7]. The rectenna used for this experiment will have the following requirements:

- 2.45 GHz frequency;
- 2 m x 2 m rectangular shape;
- 70% nominal conversion efficiency;
- dual polarization; and
- insensitivity to alignment.

The rectenna will be fabricated on a substrate using thin-film technology. The basic circuit components in each rectenna are a dipole antenna, a rectifier diode, and a lowpass filter (Figure 2). A preliminary mechanical design is given in Figure 3.

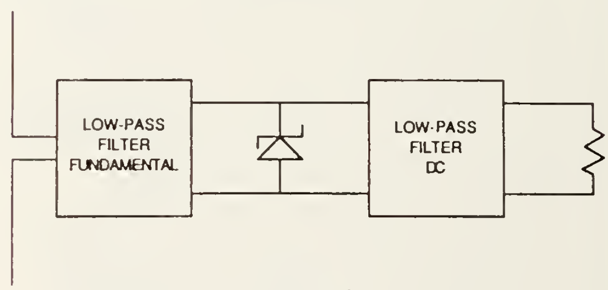

Figure 2
Standard rectenna model

Overall Efficiency:
The overall efficiency of a freespace microwave power transmission can be estimated from its subefficiencies. A basic efficiency model for the system is shown in Figure 4. Input DC power is converted to microwave power, transmitted, collected, and then converted back to DC power. The subefficiencies in Figure 4 are defined as:

(1) η_{dc}: the DC to RF conversion efficiency of the microwave generator.
(2) η_{tr}: the efficiency of the transmitting antenna.
(3) η_{ra}: the collection or absorption efficiency of the rectenna.
(4) η_{rf}: the RF to DC conversion efficiency of the rectenna.

The collection efficiency is the ratio of the power incident on the rectenna to the power transmitted from the antenna. As shown in the figure, the overall system efficiency is simply the product of these four subefficiencies, or

$$\eta_{sys} = \eta_{dc}\eta_{tr}\eta_{ra}\eta_{rf}.$$

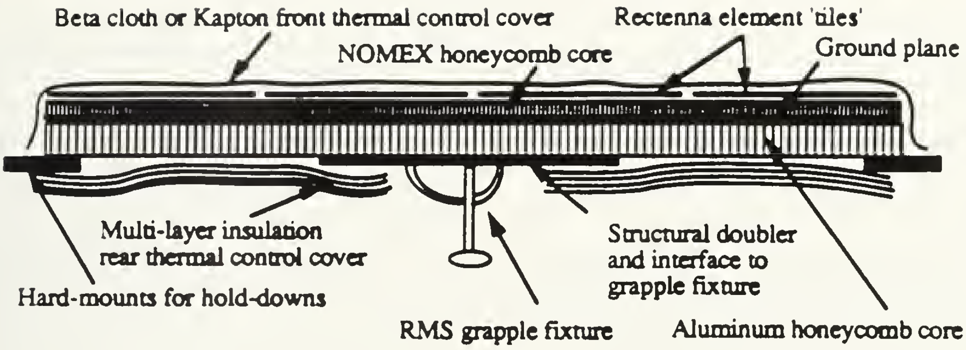

Figure 3
Mechanical layout of rectenna and its grapple fixture

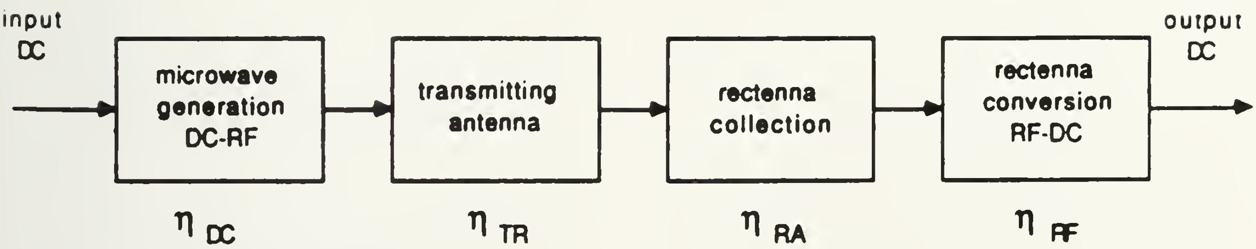

Figure 4
System functional block diagram

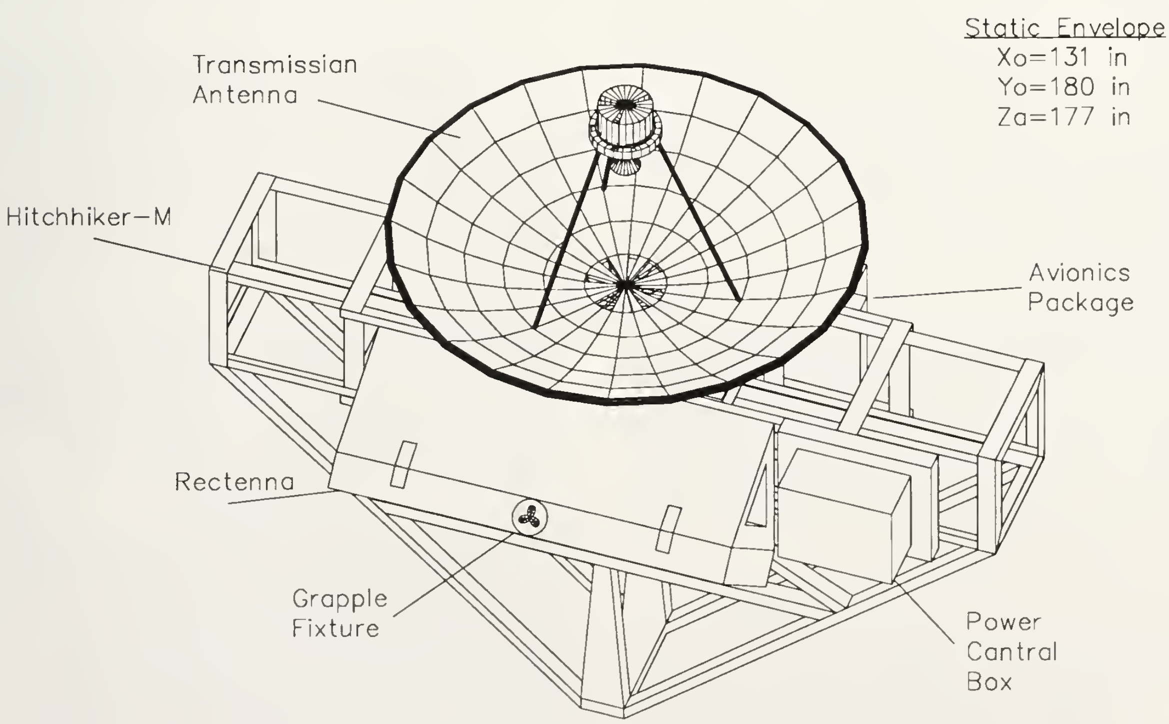

Figure 5
Antenna and transmitter on Hitchhiker-M carrier

System Integration:
The Hitchhiker-M was selected as the carrier upon which the microwave power transmission system would be mounted. The Hitchhiker-M is a cross-bay bridge type structure which can accommodate up to 1200 lbs of payload; it is situated in the Space Shuttle payload bay. Figure 5 shows the antenna mounted on top of the Hitchhiker-M carrier.

In order to provide the needed power, command and/or data for the deployed rectenna, the Hitchhiker avionics must be augmented by the RMS avionics. The Hitchhiker has a total of 1300 W of available power; the flight experiment will require 1200 W. The Hitchhiker avionics provides six experiment ports for power, command and data interface. Each experiment port contains the following:

- one 1200 baud command uplink;
- four 0-28 V discrete commands from the aft flight deck;
- one 1200 baud data downlink;
- one 1400 kbps data downlink;
- three thermistor interface;
- one 0-5 V, 8 bit, 10 Hz analog data signal; and
- two 28 VDC, 10 A power outlets.

A combination of these experiment ports will be required to meet the flight experiment needs.

The Remote Manipulator System is required to grapple the rectenna from its stowed position on the Hitchhiker-M carrier, position the rectenna at a distance of about 20 meters from the transmitting antenna, and restow the rectenna upon completion of the experiment. Data from the rectenna will be routed through wires within the RMS arm to the Hitchhiker avionics or data recorder. Ground processing of Hitchhiker downlinked data will be accomplished at Goddard Space Flight Center in Maryland. A road map for the Phase I experiment is shown in Figure 6.

Mission Scenario:
The mission scenario will be to vary the microwave power level and observe the transient and steady-state response of the system, as well as the leakage current through the plasma in a specific orbit. The attitude of the rectenna with respect to the plasma stream could be changed to establish the effects of the plasma. The environmental impacts and interference with communications will also be explored. One example would be to study the extent that side lobes would affect other users of the electromagnetic spectrum.

The expected results would be a complete definition of several important issues with respect to the use of microwave power transmission in space, such as:

(1) the efficient conversion of DC power into microwave power without an active cooling system for the generator;
(2) the performance of a thin-film, etched-circuit rectenna in the plasma environment;
(3) the determination of possible microwave interferences with other users; and
(4) the identification of possible environmental constraints including orbital drag characteristics of the transmitting and receiving antennae and plasma charging phenomena.

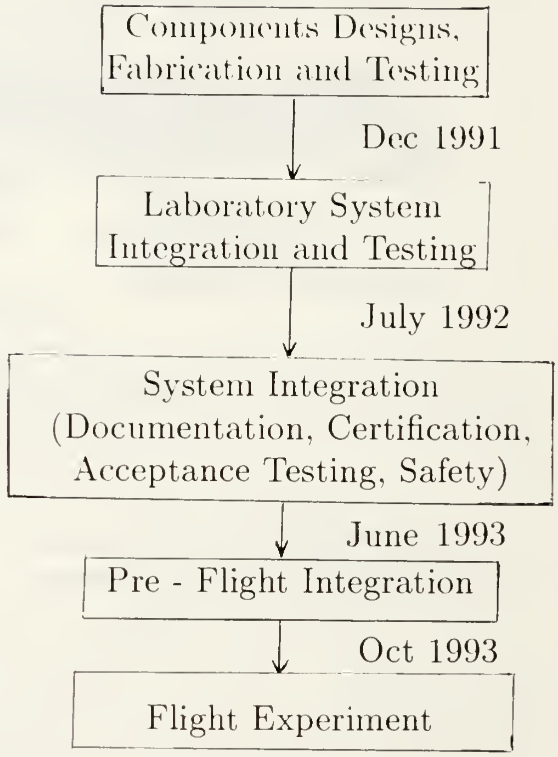

Figure 6
Road map of Phase I experiment

III. Phase II and III Experiments

Phase II will utilize much of the same hardware as Phase I, except the rectenna will be attached to a free-flying, stabilized platform operating at a significantly farther distance. This flight will develop the methods required for targeting, the establishment of a pilot beam, and the identification of requirements for spacecraft stabilization (station-keeping) in order to achieve a specified power transmission efficiency.

Phase III will involve much of the hardware, techniques and procedures from the earlier flights. Like Phase II, the transmission will be from the Space Shuttle to a free-flying platform. However, the energy will be transmitted at higher frequencies, thereby incorporating a smaller receiving, rectenna capable of operating over a greater distance.

IV. Conclusions

Transmission of power from an orbiting power generation station to one or more spacecraft has been proposed as an economic alternative to self-contained power supplies. Intra-space microwave transmission of electric power from an orbiting generating station to remote satellites utilizing standardized receiving antennae represent the flexible transmission system. Advantages would be decreased weight and volume required by the beamed power receiving equipment, resulting in a flexibility in design and utilization of the spacecraft.

The Center for Space Power has proposed a series of flight experiments aimed at proving technology necessary for microwave power transmission in space. Preliminary experiments are being carried out on a laboratory research system. The components will then be tested, certified, and assembled for the flight experiment. It is hoped that the

success of these flight experiments will pave the way for the commercialization of microwave power transmission in space.

V. Acknowledgement

The authors would like to thank Mr. William Brown of Raytheon Company and Dr. Adrian Alden of Communications Research Center, Canada for their technical assistance and suggestions. This project was supported by the NASA Center for Space Power.

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SPS 91

B1.3 Experimental Radiation cooled magnetrons for space

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ABSTRACT

The microwave generator in the Solar Power Satellite has a heat disposal problem when it converts the DC power taken from the solar photovoltaic arrays into microwave power for transmission from geosynchronous orbit to Earth. This paper addresses this general problem, provides a theoretical analysis as applied to a magnetron, and presents some confirming experimental data obtained from the QKH 2244 magnetron that was developed for an experimental beam power transmission system at the Center for Space Power at Texas A&M University.

RESUME

Le générateur microondes d'un Satellite Solaire de Puissance (SPS) présente un problème de contrôle thermique quand il transforme la puissance électrique du courant continu qui provient des panneaux solaires photovoltaïques en une puissance microondes destinée à la transmission de puissance depuis l'orbite géostationnaire vers la Terre. Cet article examine ce problème général, en donnant une analyse théorique dans le cas d'un magnétron, et il montre les résultats expérimentaux de confirmation obtenus à partir d'un magnétron QKH 2244 qui fut précisément développé pour un système expérimental de transmission de puissance par rayonnement au "Center for Space Power" de l'Université A & M du Texas.

1.0 INTRODUCTION

An important problem of all systems in space is the disposal of any heat that is generated when converting one form of energy into another form. Heat in space can be disposed of ultimately only by radiating it into space. One obvious solution to the problem is to make the energy conversion process so efficient that no waste heat is generated in the process. If this is not possible, then it is desirable to have the heat generated at a high temperature so that it can be transferred to space by taking advantage of the dependency of radiated heat flux density upon the 4th power of the radiating temperature. If there is a maximum temperature allowable for radiation, then there is an upper bound on the amount of heat that can be radiated per unit area.

The amount of heat that can be radiated per square meter from one face is given by the expression:

$$W = 5.67\ K\ (T_1^4 - T_o^4) \times 10^{-8} \qquad (1)$$

W = Watts or Joules per second

K = emissivity of surface

T_1 = Operating temperature of surface in degrees Kelvin

T_o = Ambient temperature of surrounding environment

In the Solar Power Satellite the total area available for heat radiation is the backside of the transmitting antenna

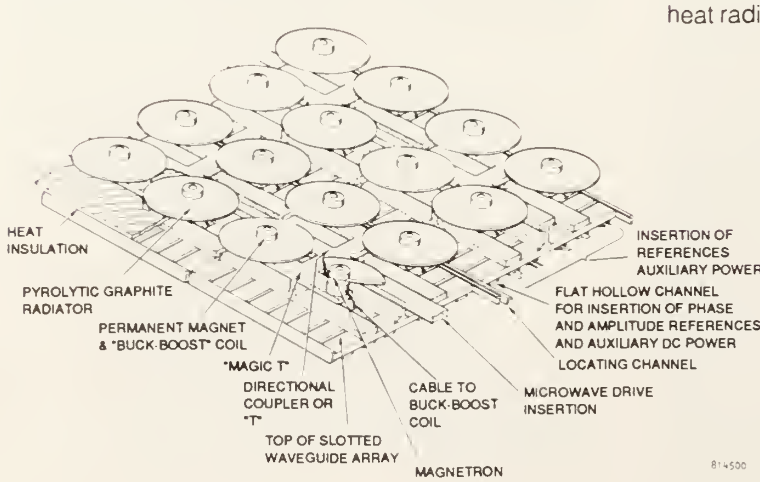

Figure 1. Assembly Architecture for the Magnetron Directional Amplifier in the Antenna Subarray at Conclusion of DOE/NASA Program. Eight Radiation Modules are Shown. The Array has Two Distinct Temperature Zones. The Top is Used to Radiate the Heat. The Bottom is Used for Mounting of Solid State Components.

which is one kilometer in diameter or 785,000 square meters in the reference design. The microwave generators are integrated into the antenna as shown in Figure 1. (1, 2) Magnetrons are shown distributed on the back of the antenna in the illustration but the same distribution would occur for other types of converters. This illustration also shows that the heat must be disposed of locally. It cannot logically be transported over long distances to other radiating sites.

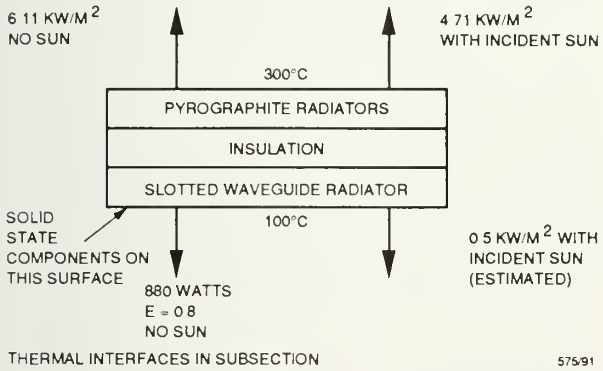

Figure 2. Thermal Interfaces in Power Module.

If the entire backside of the transmitting antenna was available for radiating heat and the insulation was perfect, the situation shown in Figure 2 would result. Assuming black body radiation, as much as 6.1 kw/m² could be radiated into black space, and 4.7 kw/m² with the complete absorption of the sun's radiant flux impinging directly upon it.

The upper bound on the amount of heat that can be radiated per unit area of the antenna and the efficiency of the microwave generator then determine how much microwave power can be radiated per unit area of the transmitting antenna. These relationships are shown in Figure 3 where contours of radiated microwave power density are shown as a function of efficiency and radiating temperature. The relationships in Figure 3 assume an emissivity K of unity (black body radiation) and radiation into a 0 degree Kelvin environment.

The radiated microwave power density is very sensitive to efficiency. If there is an upper bound to the radiated heat density , then a conversion efficiency from DC power to microwave power of 80% will produce four times the radiated microwave power density as operation at 50% efficiency. And operation at 90% efficiency, a distinct possibility at 2.45 GHz and already achieved at 890 MHz, will produce nine time as much power output as operation at 50% efficiency. (3) In addition, the radiated microwave power density is sensitive to the temperature at which waste heat is radiated. A device operating its allowable heat disposal area at 300 degrees Celsius will generate 5.5 times as much microwave power as one operating at 100 degrees Celsius. It follows, therefore, that a device that is both highly efficient and which can feed heat into its allowed heat disposal area at a high temperature has a great advantage over a moderately efficient device operated at a low temperature.

It may be of interest to apply Figure 3 to a scenario in which the transmitting antenna is radiating 7 gigawatts of power to produce 5 gigawatts of DC power output at the rectenna on the ground. The average radiated power density over the 785,000 square meter antenna (one kilometer in diameter) is then 8.9 kw/m2. However, the distribution of transmitted power over the face of the antenna to reduce sidelobes will approach that of a truncated gaussian for which the peak to average power may be about 3. The corresponding peak radiated power density at the center of the antenna is then 27 kw/m². Now, if figure 3 is examined it is noted that 27 kw/m² is near 32 kw/m² radiated power density that requires both high efficiency of the microwave generator (85%) and high radiating temperature of 300° C (573° Kelvin).

It is also desirable that the conversion device be cooled by direct passive radiation into space rather than being indirectly connected to the heat radiator with a liquid or vapor cooling system. Active cooling systems have a reliability disadvantage because of the danger of being punctured by passing debris which would create a vapor which could be ionized by the microwave or high voltage DC power and cause electrical loss and breakdown.

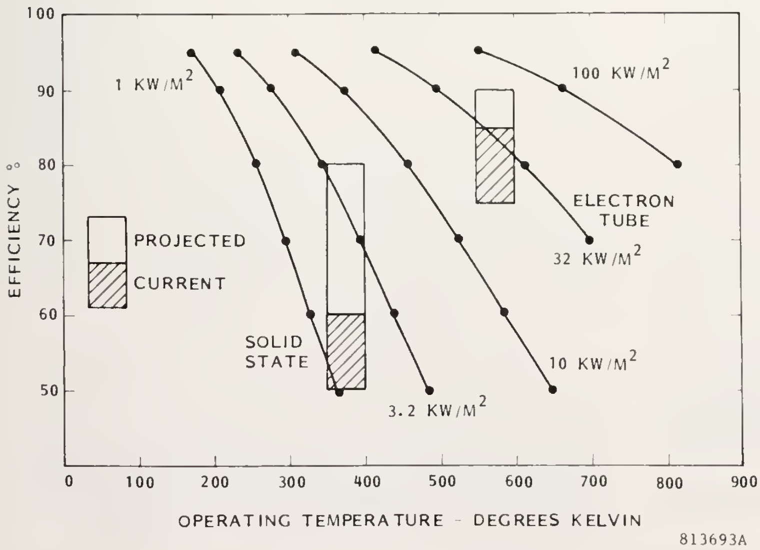

Figure 3. Contours of Microwave Power Outputs as Function of Efficiency and Operating Temperature of Microwave Generators.

2.0 THEORETICAL STUDY OF THE RADIATION COOLING OF A MAGNETRON DIRECTIONAL AMPLIFIER

During the NASA/DOE sponsored study of the Solar Power Satellite in the 1977 to 1980 time period, the magnetron with its high efficiency, mechanical simplicity, and ability to behave as a phase-locked amplifier with added external circuitry was evaluated as a candidate for the microwave generator in the Solar Power Satellite. (1,5) This study, in combination with studies of a slotted waveguide array, produced a design of a radiating module like that shown in Figure 1. As shown in Figure 1, the magnetrons with their circular radiators are thermally isolated from the front of the radiating module so that solid state sensing and control devices can be placed on the front of the array . This allows the tubes and their radiators to be operated at high temperature on the back side of the array although the radiators can radiate effectively from one face only.

The earliest studies on the microwave generator tube for the SPS quickly zeroed in on pyrolytic graphite (also referred to as "pyrographite") as a preferred material for the radiator. (1,4) In the range of 100 degrees to 300 degrees Celsius the annealed or heat-treated pyrolytic graphite has a heat conductivity twice that of copper as shown in Figure 4 and it has a density of only 2.0 as contrasted to 8.9 for copper. Further it has a natural emissivity of 0.92 and a negligible vapor pressure at the intended operating temperature. It was also assumed that for purposes of data computation the radiator was radiating into deep space with a temperature of near 0 degrees Kelvin.

A factor that greatly simplifies the study of a specific pyrolytic graphite radiator design is the relationship of its size to that of the slotted waveguide radiator. The dimension of the heat radiator has to match the dimensions of the slotted waveguide radiator associated with it in the radiation module. The dimensions of the slotted waveguide radiator are quantized. It is assumed that each waveguide stick must have an even number of slots in it and each set of slots is approximately 18.4 centimeters long. The dimensions of the area occupied by the magnetron directional amplifier and its associated waveguide section could therefore be 18.4 cm. 36.8 cm., 55.2 cm., 73.6 cm. etc. These dimensions are also associated with the number of waveguide sticks in the array of 2,4, 6, and 8 respectively as suggested in Figure 1.

For the same temperature drop in the radiator from the center to outside edge the mass goes up as the fourth power of the diameter while the heat radiated goes up as the square. This relationship causes an unfavorable increase in the mass of the radiator per unit of heat radiated as the size of the radiator is increased. Also the cost of the pyrolytic graphite per unit of heat radiated would increase with the diameter as would the cost of transportation into orbit. While the 55.2 cm diameter would be unfavorable from this point of view, the 18.4 dimension is probably much too small from the viewpoint of the greatly increased number of radiating modules that would be required, and also from the viewpoint of the difficulty of designing a magnetron that would operate with one kilowatt of power output at an anode voltage of 20 kilovolts. (The high voltage is a requirement of the system to reduce electrical bus losses). The magnetron design is therefore based on the dissipation capability of a pyrographite radiator 36.8 cm in outer diameter and 5.5 cm inner diameter, and tapered as shown in Figure 5. The power level of the associated magnetron is about 4 kilowatts.

Given the dimensions of Figure 5, an assumption of radiation from one side only, and an emissivity of 0.92, the method of determining the total heat radiated and the temperature drop from the center of the radiator to its outer edge follows (1) divide the radiator into a large number of radial segments for computation purposes, (2) assume an average temperature for the outermost segment, (3) compute the heat radiated from the outermost segment, (4) compute the temperature drop associated with the radial flow of heat through the ring, (5) add this temperature drop to the radiating temperature of the outermost segment, (6)

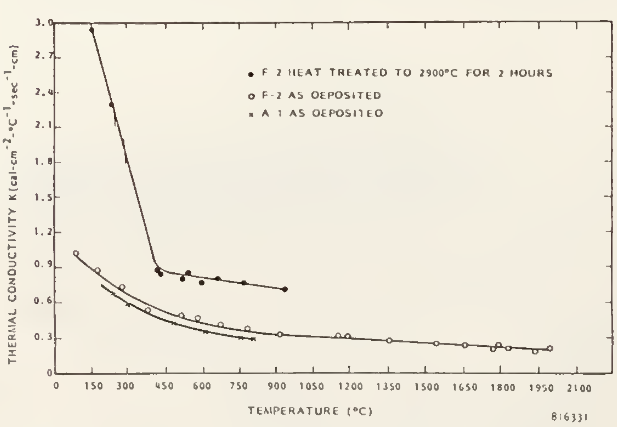

Figure 4. Thermal Conductivity of Pyrographite in the "a" Direction as a Function of Temperature.

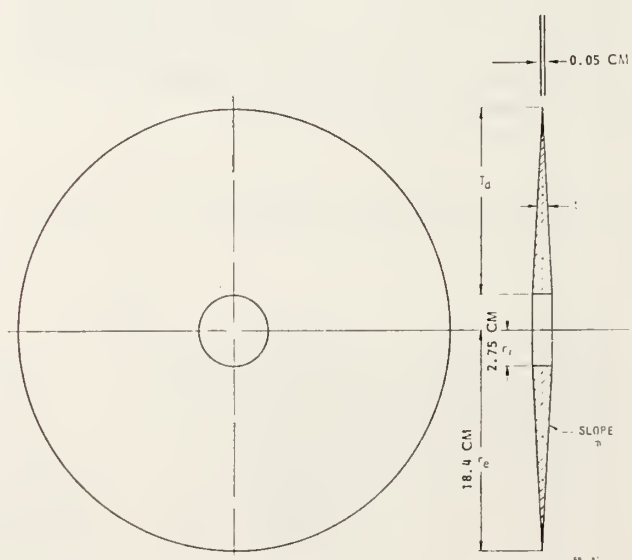

Figure 5. Drawing of the Shape of the Cooling Fin for the Microwave Generator. Heat Flows Radially from the Magnetron at the Center and is Radiated from the Top Surface Only.

using the resulting temperature compute the heat radiated by the segment next to the outermost segment, (7) add this heat radiated to that radiated by the outermost segment, (8) using the resulting heat compute the temperature drop associated with its radial flow through the segment , (9) repeat the previous procedure for all segments. As the radius becomes less, the temperature will become greater until the maximum temperature is reached at the inside edge of the radiator,. The temperature rise will obviously be a function of the amount of taper and also of the temperature itself as the heat conductivity varies with temperature, as shown the individual segments.

To obtain the appropriate data, it is necessary to run a large number of these computations in which the temperature at the outer edge is varied and in which the degree of taper is varied. From a practical point of view, the outer edge of the radiating fin would have to have some thickness. In the calculations a thickness of 1/2 millimeter or 0.020 inch was used. The results of the computerized computation are shown in Figure 6.

Shown in Figure 6 are contours of a constant value of temperature at the inner radius, because this temperature may be the limiting condition imposed upon operation of the magnetron. To illustrate the use of the curves, select the contour that gives the desired temperature at inner radius of radiator. Then select the desired value of power to be dissipated from those given as ordinate values along the left side of the figure. Then horizontally project this value to the right until it intersects with the inner radius temperature curve. The vertical projection of this point determines both the thickness of the radiator at its inner edge and the mass of the radiator in grams. Temperature at the outer edge of the radiator may also be determined from the four contours of constant outer edge temperature.

To illustrate the use of the curves, consider a decision to use a maximum temperature of 340 degrees Celsius at the inner radius, and also the need to dissipate 560 watts of power. To find the mass of the radiator and its thickness at the inner radius, project horizontally the ordinate value of 560 watts until it intersects with the 340 degree constant temperature contour of the inner radius. Then drop a line vertically from this point of intersection to intersect the radiator mass curve to give a mass of 325 grams for the radiator. The radiator mass represents about 1/3 the mass of the complete magnetron directional amplifier with a nominal microwave power output of 4 kilowatts. (Table 7-2 of Reference 1 or Table 2 of reference 5). Then to obtain the thickness at the radiator's inner radius extend the vertical line down to the abscissae values of radiator thickness at the radiator's inner radius to determine the inner radius as 0.36 cm.

The radiator mass goes up very rapidly with dissipation requirements if there is an upper limit on the temperature of the radiator. For example, a requirement of 400 watts of dissipation rather than 560 indicates a vane thickness of 0.2 cm at the inner radius and a mass of 145 grams. Thus an increase in dissipation by a factor of 560/400 or 1.4 leads to an increase in radiator mass of 325/145 or 2.24

A mechanical mockup of the fin attached to a tube is shown in Figure 7. The heat generated within the magnetron by inefficient energy conversion from DC power to

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Figure 7. The Magnetron is Cooled by Flow of Heat Into a Pyrolytic Graphite Radiator which Radiates Heat Directly Into Space. Pyrolytic Graphite has Three Times the Conductivity of Copper but Only One-Third its Density, and has an Emissivity Approaching that of a Black Body.

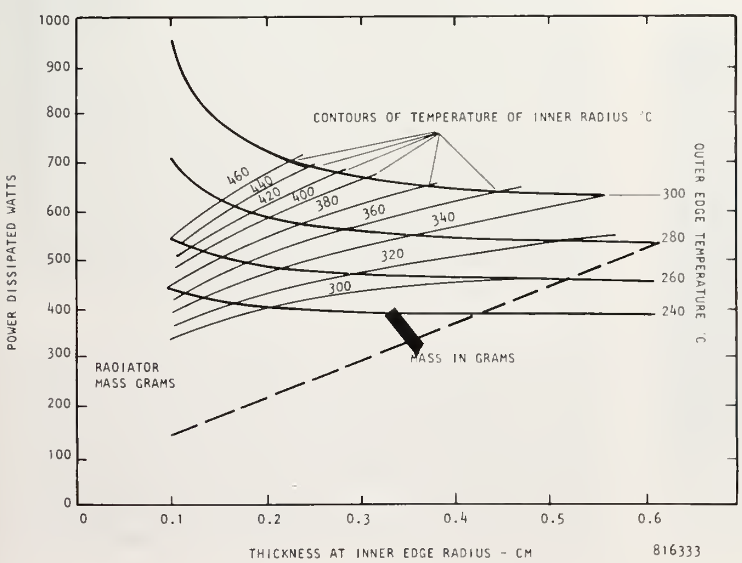

Figure 6. Information Chart for Selection of Pyrographite Radiator and Determination of its Mass. First, Determine Desired Temperature at Inner Radius of Radiator. Then Select the Desired Value of Power to be Dissipated by the Radiator and Project this Value Horizontally Until it Intersects with the Inner Radius Temperature Curve. Vertical Projection of this Point Determines Both the Thickness of the Radiator at its Inner Edge and the Mass of the Radiator in Grams. Temperature at Edge of Radiator may also be Estimated.

microwave power flows uniformly to the outer cylindrical shell of the magnetron. The heat then flows into the external radiator that is bonded to the magnetron. (5)

3.0 DESIGN AND EVALUATION OF THE QKH 2244

The preparation for a proposed demonstration of beamed microwave power transmission aboard the space shuttle, sponsored by NASA and its Center for Space Power at Texas A&M University, included the procurement of such a radiation cooled magnetron, designated the QKH 2244. The QKH 2244 magnetron is shown in Figures 8, 9 and 10. Figure 9 shows the QKH 2244 attached to a section of waveguide.

The QKH 2244 is basically a microwave oven magnetron that has been fitted with a fin to cool the operating magnetron in a vacuum or space environment. The particular microwave oven magnetron chosen as the tube portion of the QKH 2244 was the Hitachi 2M170. The tube was stripped of its external hardware and magnets before adding the radiator. Although the microwave oven magnetron converts DC power to microwave power with high efficiencies of 60% to 70%, the remaining part of the DC input power appears in the form of heat and must be disposed of.

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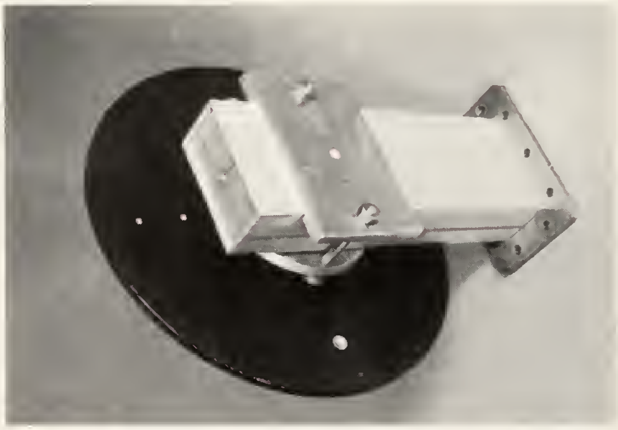
Figure 8. QK 2244 Radiation Cooled Magnetron Showing Output Antenna which Radiates its Power Into a Waveguide.



90 2570C

Figure 9. QKH 2244 Radiation Cooled Magnetron Fitted with Waveguide Output Transition for Coupling Into 1.4" x 3.0" Waveguide.

90 2568C

Figure 10. QKH 2244 Radiation Cooled Magnetron Showing Attachment of Shielded Power Input Cable Supplying Cathode Heater Power and Anode Power.

It is intended to operate the QKH 2244 as a free running oscillator in the proposed demonstration of beamed power transmission. However, it is easy to convert its operation into that of a high-gain, phase-locked amplifier with external circuitry . The operation then is closely analogous to its use in the transmitter of the Solar Power Satellite as shown in Figure 1.

The major design items that are novel in the QKH 2244 are the radiating fin and the magnetic field circuit.

3.1 Design and Testing of the Radiating Fin

The design of the fin was dependent upon the specified microwave power output for the proposed demonstration, the efficiency of the magnetron, and the temperature at which the fin could be operated. The required power output was 250 watts. At a nominal efficiency of 60%, this would require the fin to radiate 167 watts. A maximum operating temperature of 300°C at the anode of the tube was also assumed, but this selection is somewhat arbitrary and conservative. To make the design itself conservative, the objective dissipation of the fin was taken to be 240 watts, and the fin was evaluated at this level.

The end objective of the fin design is to minimize the radiating area and the mass of the fin. To obtain this objective, the material of the fin should have a very high ratio of heat conductivity to its density, and its surface should have a very high emissivity. Also the tapering of the thickness of the fin can reduce the mass. As was pointed out, pyrolytic graphite with its low density, very high heat conductivity, and near black body emissivity is an ideal material for a radiating fin. However, in the context of the modest funding available for the tube construction, its high cost prohibited its use. It was therefore necessary to look for alternative materials in designing the fin.

After a literature study of various materials and their treated surfaces was made it was decided to experimentally evaluate a black dyed anodized surface on aluminum that was available form a local vendor. This turned out to be a fortuitous choice but at the time of procurement it was not known whether such a surface would hold up at an operating temperature of 300 degrees Celsius in vacuum,

or if it would degas to such an extent as to ruin the exhaust system in which it was inserted.

To expedite the procurement of anodized disks, the disks to be anodized were fabricated in the most expedient way without regard to such refinements as tapering. Further, the diameter was limited by machining considerations to a diameter of 9 3/4". These test disks, however, gave a performance that met the radiation objective of 240 watts of heat at a temperature below the specific 300 degrees Celsius and so, in the interests of cost and time saving, they became incorporated into the final design of the tube. However, the design of the fin is far from being optimized. In particular the fin thickness is much greater than it has to be, but the fin was left thick so that the radiating temperature over the fin would tend to be more uniform and thus make it possible to more accurately determine the emissivity K of the surface.

To determine the characteristics of the anodized surface in the vacuum bell jar it was necessary to have an adequate heat source at the center of the fin. The magnetron itself can perform this function without the generation of microwave power whose absorption in a vacuum becomes a difficult problem . To employ the magnetron as such a heat source, the permanent magnets are removed from the tube and it is operated as a simple cylindrical diode, in which the current flow between cathode and anode is proportional to the 3/2 power of the applied voltage. However, it was necessary to transfer the heat from the shell of the magnetron to the cooling fin under evaluation. This was accomplished by first press fitting a copper ring to the magnetron shell and then bolting the copper ring to the anodized aluminum fin.

The use of the vacuum bell jar for the tests is shown in Figure 11. The pumping system employs a centrifugal pump of good capacity and was able to achieve a vacuum of 10^{-5} millimeters of mercury during the tests on the anodized aluminum surface. Of prime importance in the evaluation tests were the emissivity K of the surface and the stability of the surface and its retention of a high emissivity over a period of time.

The evaluation was simply instrumented by monitoring the power input to the magnetron and noting the temperature of the cooling fin. The power input was the power required to heat the filament to an electron emission temperature plus the product of the applied anode current and anode voltage. The temperature of the fin was monitored by a thermocouple placed at a distance of 1" from the outer edge of the fin. In addition a thermocouple was placed on the copper ring. A difference in temperature of the two thermocouples then represented the temperature drop between the copper ring and the cooling fin, plus the drop in fin temperature from inner to outer radii.

The procedure in testing a new radiating fin was to increase the fin temperature at a rate at which the degasing of the fin did not saturate the pumping system. After this intial processing, which could require half an hour, the fin was ready for evaluation. The evaluation procedure was to suddenly apply a total input power of 240 watts and observe the transient buildup of temperature at the points A and B, as shown in Figure 12.

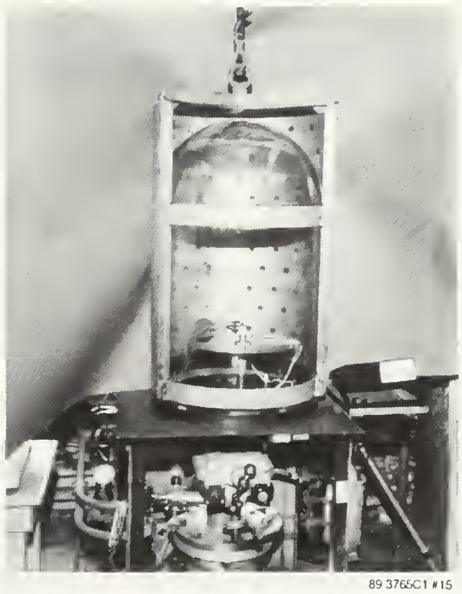


Figure 11. Arrangement for Experimentally Determining the Characteristics of the Black Anodized Aluminum Radiating Fin in a Vacuum Environment. Magnetron Without Magnetic Field is Used as a Cylindrical Diode to Generate the Required Flow of Heat to the Fin.

Figure 12 indicates the transient response of temperatures at A and B to the step function of 240 watts of power input to the anode. It is seen that the steady state fin temperature reaches a temperature of about 225 degrees Celsius. The time duration of the data shown in Figure 12 is 44 minutes, but in several cases the time period was extended to several hours without a change in temperature of the fin, indicating that the emissivity had not changed during those time intervals.

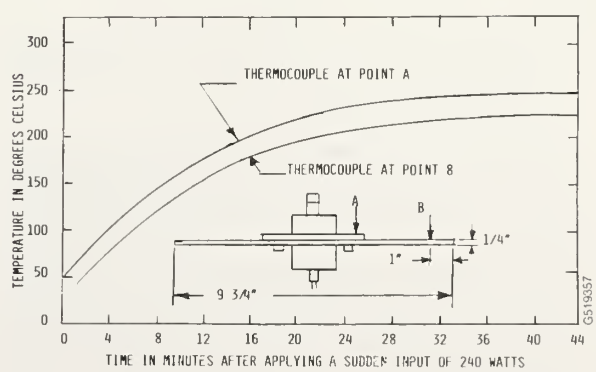


Figure 12. Transient Response of the Temperature of the Black Anodized Aluminum Radiating Fin to a Sudden Input of 240 Watts to its Inner Radius. Temperature Sensors were Placed at Locations A and B.

It was not possible to make long term tests lasting several days on the cooling fin, but it seems to be evident that the fin is suitable for demonstration tests such as those being proposed for the shuttle which are of short duration. However, a continuous test of nearly four days (ninety hours) was made on the same anodized surface at a temperature of 115 degrees Celsius without any noted

deterioration of the emissivity. These tests were made in the context of cooling a diode rectifier in a rectenna array and involved a radiating fin that was 5 cm in diameter and 0.05 cm thick.

Two magnetron radiating fins of the same design were tested in vacuum. Both of these fins were subjected to a large number of transient temperature buildups, and total operation in both cases amounted to several hours. There was no indication that the anode temperature on successive runs was increasing, thereby also indicating that the emissivity K was not changing.

A calculation of the emissivity K was made, assuming that (1) all of the input power of 240 watts to the magnetron was conducted to the fin and radiated from it, (2) that the effective area of the radiating fin consisted of an area consisting of both sides of the fin and a radial fin dimension extending from the magnetron anode radius to the outer edge of the fin, (3) the average operating temperature of the fin is 235 degrees Celsius, or about 10 degrees hotter than the rim temperature, and (4) that the surrounding temperature environment was 27 degrees Celsius. Putting these values into expression (1), the K is calculated to be 0.785. This is a high value of emissivity for a surface, and indicates that a black dyed anodized aluminum surface may be an excellent radiating surface at high temperatures in space if pyrographite is not available.

Aluminum material is also an excellent choice if the mass is to be minimized. Aluminum has a heat conductivity of 0.55 calories per second per cubic centimeter per degree Celsius at 200 degrees Celsius compared with 0.97 for copper, but its density is 2.7 as compared with 8.9 for copper. Therefore, for a fin of equal conductivity the thickness needs to be increased in the ratio of 1.76 for aluminum. However the total mass of the radiator will be down in the ratio of 1.87, in favor of aluminum.

3.2 Designing and Acquiring Suitable Permanent Magnets for High Temperature Operation

The conventional microwave oven magnetron uses ceramic type permanent magnets that adequately fulfill their mission if the magnetrons are operated at reasonable temperatures. However, they will not be at all satisfactory at high temperatures. Alnico type magnets would easily withstand the high operating temperature but their use would greatly complicate the design because they would have to be added as a "C" or "E" type magnet which would penetrate through large circumferential sections of the radiating fin. Alnico magnets would also represent a large amount of mass which would be objectionable for space use. Replacing the ceramic magnets with Rare Earth Cobalt ring magnets of the same thickness, but of smaller diameter, has helped, but there is little margin left for operation of the magnetron at higher temperatures than 300 degrees Celsius without a serious reduction in the magnetic field and therefore an accompanying drop in operating anode voltage and efficiency.

The rare earth cobalt magnets that were used were ring magnets 2 inches in outside diameter and 3/8 of an inch in thickness. They are made from grade 18 material, which has a specified "maximum practical operating temperature" of 225 degrees Celsius. They may therefore be marginal, or even inadequate, depending upon the actual microwave power required from the tube. Thus far, it has been impractical to operate the magnetron with integral magnets in a vacuum because of the microwave power disposal problem.

Even though the currently used magnets may present a potential problem there is a new generation of rare earth magnets that are becoming available and which have a maximum useable temperature range of 300 to 350 degrees Celsius, a full 100 degrees greater than the previous generation. This new material also has a higher energy product which will reduce the size of the magnet that is needed. These new magnets are described on page 930 of the June 1990 Special Issue of the Proceedings of the IEEE on Magnetics in an article by Karl Strnat.

3.3 Typical Electrical Performance of the Radiation Cooled Magnetrons

QKH 2244 serial #1 exhibited the performance in Table I when it was operated into a conventional waterload where its microwave power output could be measured. In examining the table the reader is reminded that "efficiency" is defined as the ratio of microwave power output to DC power input to the anode only. "Dissipated Power" includes the power input to the filament which in turn is radiated in the form of heat to the magnetron anode and constitutes an addition to the heat that must be disposed of by the radiating fin.

4.0 CONCLUSION

The experimental QKH 2244 magnetron, identified as an unpackaged microwave oven magnetron to which an anodized aluminum radiator has been attached, and whose magnetic field has been supplied by special samarium cobalt magnets, has been evaluated for its ability to directly radiate into space the heat resulting from the inefficiency of the DC to RF conversion process. The design of this tube with respect to the radiation of heat is closely analogous to that of tubes designed for use as the microwave generator in the Solar Power Satellite, and therefore represents a useful step in the evolution of such a tube for space use.

5.0 ACKNOWLEDGEMENTS

The authors acknowledge the support of the work reported in this paper by the NASA Center for Space Power at Texas A&M University and the Raytheon Company.

TABLE I

E_f volts	I_f amps	V_a kv	I_a ma	Power Input watts	Microwave Power watts	Efficiency %	Dissipated Power watts
2.6	12	3.58	100	358	188	52.0	222
2.6	12	3.52	150	528	314	59.5	266
2.6	12	3.50	200	700	424	60.5	328
2.6	12	3.47	250	867	550	63.4	369
1.2	5	3.59	10	359	204	57.0	161
1.2	5	3.59	150	538	330	61.3	214
1.2	5	3.59	200	718	425	59.2	299
1.2	5	3.53	250	882	551	62.4	336

(1) W.C. Brown, "Satellite Power System (SPS) Magnetron Tube Assessment Study, "NASA Contractor Rep. 3383, Contract NAS8-33157, Feb. 1981.

(2) W.C. Brown, "Update on the Solar Power Satellite Transmitter Design." Space Power, Vol. 6, pp 123-135, 1986

(3) J.R. Twisleton, "Twenty-Kilowatt 890 Mc's Continuous Wave Magnetron, "Proc. IEE, Vol. 3, No. 1, pp 51-56, Jan. 1964.

(4) J. Pappis and S. Blum, "Properties of Pyrolytic Graphite" Journal of the American Ceramic Society, Vol. 44, No. 12, 1

(5) W.C. Brown, "The SPS Transmitter Designed Around the Magnetron Directional Amplifier." Space Power, Vol. 7, No. 1, 1988 pp 37-49.

SPS 91

B1.4 An evolutionary satellite power system for international demonstration in developing nations

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Abstract

The ISAS solar power satellite working group is working on a concept of an SPS strawman model for demonstration of electric power supply to customers at the earliest opportunity. The SPS is modularized, so that each unit can be launched by a commercial launcher to an equatorial low earth orbit where it is assembled automatically. The satellite can supply electric power by microwave to rectennas at every pass. Based on this model, technological and programatic characteristics of a small SPS are discussed.

Résumé

Le Groupe de Travail "SATELLITE SOLAIRE DE PUISSANCE" de l'I.S.A.S. étudie actuellement un concept de SPS de taille réduite en vue de la démonstration, dès que possible, de la possibilité de fourniture de puissance électrique à des clients. Ce SPS miniature est modulaire, ainsi chaque élément peut être mis en orbite équatoriale basse par un lanceur commercial, pour être assemblé avec les autres modules automatiquement. Le satellite ainsi assemblé peut fournir de la puissance à des rectennas par microondes à chacun de ses passages. A partir de ce modèle, les caractéristiques technologiques et programmatiques d'un mini SPS sont discutées.

Introduction

The SPS Reference System was designed for the SPS Concept Development and Evaluation Program (CDEP) of the U.S.A., to study the wide range of problems anticipated when such a system is introduced as a national power system of the world's largest industrialized country. As a result, many understandings have been obtained, and uncertain issues needing to be studied further have been indicated. The study concluded that the system was technically feasible and further study is required (1 and 2).

The ISAS Solar Power Satellite Working Group is interested in a much smaller SPS as a strawman model study, which will be introduced and discussed in this paper. At first, We will explain briefly about the working group as the background of the strawman model study.

ISAS SPS Working Group

ISAS which is responsible for implementation of the Japanese space science program provides researchers of universities and government agencies with convenience of nationwide research activities. A working group of the organization usually functions as a group to develop a concept of and conduct definition studies on a space mission. The purpose of the SPS working group established in 1987 was different from the other working groups, since it never intended to plan an SPS project for ISAS but, to remain as a research group to investigate the feasibility of "power from space" which was shown by the CDEP and the Reference system. The Scope of the SPS Working Group is described as follows:

"The solar power satellite was proposed (by Glaser) to solve future problems caused by activities of human beings on the global scale (3). The research areas of SPS are concerned with not only technology and engineering, but also big problems such as "large scale project", "global energy production" and "exploitation of extraterrestrial resources", as well as economical problems such as "large scale and long-term investment" and "risk analysis". The earth environment, which will be related

to SPS, is already a societal issue of global scale.

Many research areas are beyond the capacity of the working group. The primary objective of the working group is not to plan an operational SPS, such as the DOE/ NASA Reference System. As indicated by the US study, researches are most important at the present. In this respect, the members of the working group should find out a common interest in connection with the future of SPS, and make plans for space experiments along with a scenario of research and development for SPS. It should be emphasized that the development of high power technology for space use is not the main objective of the research".

The working group is divided into thirteen subgroups by specialized research fields. Nine of them are concerned with studies on SPS subsystems and technologies. Other four subgroups are for studies on the effects of interaction of the SPS operation with the environment. The individual research fields of the thirteen subgroups are listed as follows;

Study on Subsystems and Technologies
- Microwave transmission
- Microwave reception
- Large space structures
- Guidance and control
- Laser technology
- Photovoltaic technology
- Thermodynamic power generator
- Propulsion
- Space robotics

Study on Environmental Interaction Effects
- Spacecraft environment
- Space electromagnetic environment
- Communication systems
- Biology and ecology

It is noted that the working group is not a task force type of organization that should be functionally organized to accomplish a certain duty given from outside, but a group of researchers who are interested in various aspects of SPS. Thus, the subgroups have been voluntarily organized by researchers with common interests in each, and are coordinated as a working group. One of the research areas is concerned with the strawman model concept.

The strawman model study guideline

The results of the CDEP give us a basic reference for interpolation of the growth of SPS from the present. The first problem the working group faced was that each member researcher could not find a definite image of his research related to the CDEP reference system. Then it was proposed to conceptualize what they would consider a more realistic SPS in terms of their research subjects. As a result of discussion, the size of the model should be as small as can be realized by the present space technology and space infrastructure, but should be large enough to be considered as an SPS.

A 10 MW model once studied by an industry study group was known and reexamined by the group. The original concept was substantially a smaller version of the Reference Model, which was built in a low earth orbit and transported to the geosynchronous orbit for operational tests. The mechnical configuration and power transmission method are similar to those of the Reference System, which used solar panel and antenna structures connected by a gimbal mechanism with a slip ring (4).

In the guidelines for the new 10 MW model study, a low earth equatorial orbit is chosen for all the operations and the gimbal mechanism is eliminated. The primary reason to use the orbit is to make it possible to use launch systems available in or before 2000

Consequently all the rectennas will be sited in developing countries located in the equatorial zone. This assumption implies the objective of this system is more than an experiment and could include evaluation of a pilot plant of SPS for power supply to the earth. Overall, the concept emphasizes demonstration of electric power supply to customers at the earliest opportunity rather than being designed first for research and development.

This model of SPS is intended to be realized as soon as possible. In this respect, most of the technologies employed are conventional or available in the near future. This means that the performance of the SPS is allowed to be relatively low, for example with high specific mass, low efficiencies of power conversion and transmission. The few exceptions are the significant amount of space assembly work with multiple launches, and high technology for beam control. The latter is concerned with the operational constraints due to low earth orbit that is the most crucial point of this system for final evaluation. Although the microwave frequency to transmit microwave power to a rectenna on the ground is the same as the Reference System, the beam has to sweep more widely to track ground rectennas while it passes over them.

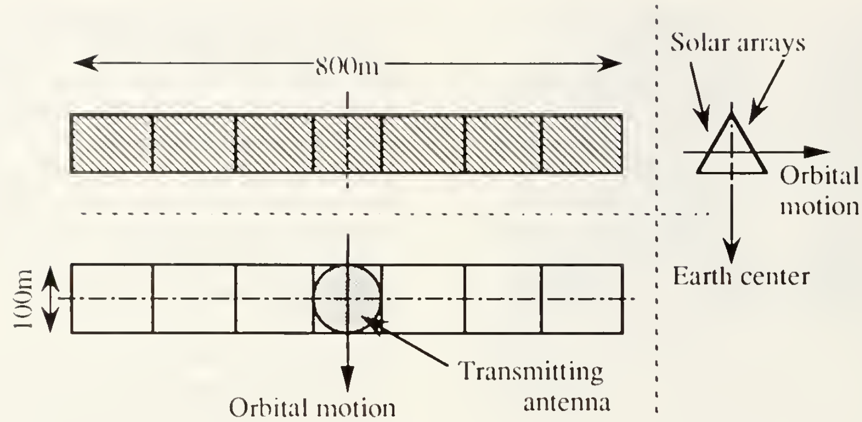

Fig. 1. General configuration of SPS 2000

SPS 2000 system

There have been several general configurations proposed at the initial study phase. The following system designated as SPS 2000 is based on one which features the gravity gradient attitude stabilization of the entire system.

General configuration
The general configuration of SPS 2000 has the shape of a triangular prism with a length of 800 m and sides of triangle of 100 m as shown by Fig. 1. The prism axis is in the north-south direction, perpendicular to the direction of orbital motion. The transmitting antenna is fixed to the bottom surface facing to the earth, and the other two side surfaces are used to deploy the solar arrays. No energy storage for power transmission during eclipse is provided.

The reason this configuration is adopted is easiness of construction of the system in orbit as well as of orbital operation under the gravity gradient force which is larger in a low earth orbit (LEO) than in the geosynchronous earth orbit (GEO). On the other hand, the requirements of high efficiencies in terms of power conversion and mass reduction, which have been generally accepted for space system design, are not considered to have high priority in this study.

Structure design
A conventional rigid beam structure is assumed for the main structure of pyramid shape. The function of the structure is to deploy the solar array and the phased array antenna, and to provide the subsystems with references of geometrical locations. Since accuracy of shape is not required, the strength of the beam was determined considering the forces caused by off-center-of-gravity forces including gravity gradient torque and the attitude control force. A standard beam of the structure is 100 m long and the cross section is triangular with sides of 3m. The fundamental element of the structure is aluminum pipe with an outer diameter of 12 mm and 0.5mm wall thickness. The total mass of the structure is 4 tons.

Power conversion and distribution
The solar array consists of about 1500 rolls of 1m x 100 m strips of solar panel, which will be stretched between the top longitudinal beam to the lower beams of the main structure. Conversion efficiency of the panel is assumed to be 14 %. Then each strip of solar panel generates 1 kV x 20A of DC electrical power at maximum. The panels are electrically connected to each other in parallel. The cable network of the system is used not only to conduct the electrical current to the transmitting antenna but also to serve as magnetic torquers for attitude control of the overall system. The power conducting cable is one of the heaviest elements of the system, especially in the case of the high power density antenna.

Transmitting antenna
Transmission is possible only when a rectenna is in the field of view of the controllable microwave beam, which is assumed to be movable as much as 30 degree in any direction from the center position. Therefore, a rectenna located on the equator can receive power from a single satellite in a 1000 km equatorial orbit for 200 seconds in one orbit, and about 1600 seconds in a day. The relation of diameters of the transmitting antenna, Dt and rectenna, Dr

and distance between them, d is given for transmitting frequency f (MHz) as;

$$f \times Dt \times Dr / d = 0.68 \quad \text{(length in km)},$$

In this case where d is approximately 1100 km, typical values of Dt and Dr are 100m and 3 km respectively. If Dr is as large as that of the Reference System, Dt is only 30 m. One of the concepts of the antenna based on a current design (5) is shown by Fig. 2.

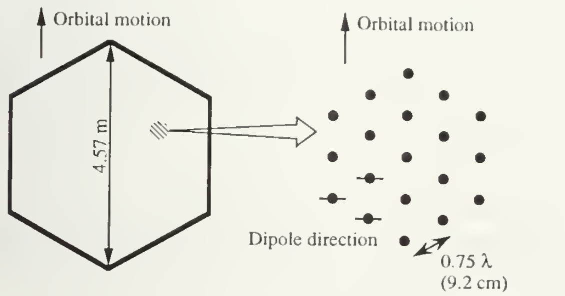

Fig. 2. A concept of transmitting antenna subarray for SPS 2000.

Guidance and control

Reduction of the operating cost has been selected as the primary requirement of the guidance and control system design. From the standpoint of spacecraft design, easy orbit management and simple attitude and thermal control systems are desired to satisfy this requirement. To make this approach possible, the electrical power system should be operable over a wide range of conditions of the related factors. The standard orbit altitude is 1000 km for this study, although it may be subject to change to 800 or 1200 km to avoid the most crowded altitude of 1000 km. The annual loss of altitude for these altitudes is several km, which will be acceptable for a decade or more period of operation without orbit maintenance. The gravity gradient force will be used to keep the system vertically in the orbital plane. Attitude keeping in the north-south direction can be achieved by the restoring magnetic force of the electric current loop in the geomagnetic field. Active control may be necessary if periodical forces caused by non-uniformity of the geomagnetic field could act resonantly on the structure.

Assembly work and operation

Considering the complete assembly of SPS 2000 is much larger than the present launch systems, and the mass would be more than the payload of even the Energia launch vehicle, the SPS has to be divided into several flight units and deassembled to be packed in a payload envelope of a launch system. In the preliminary study, Arianne 5 launch vehicle has been assumed for the transportation, mainly because of its ease of access to an equatorial orbit. A launch capability of the vehicle into 1000km high altitude orbit has been predicted to be approximately 12 tons, based on an available standard data (6). According to the same data, the payload envelope is of cylindrical shape of 4.57 m diameter and 12 m length with a conical space on the top. An example of mass breakdown of a payload is shown in Table 1, which is a design target with a margin of 2 tons for one flight unit of SPS 2000. Each unit will consist of a modular portion of every subsystem of the completely assembled system, and can be

Table 1. Mass breakdown of integrated payload for the first flight unit of SPS 2000

Item	Mass (ton)
Transmitting antenna	5
Solar array	3
Main structure	0.5
Cable and and bus	1.5
Total	10

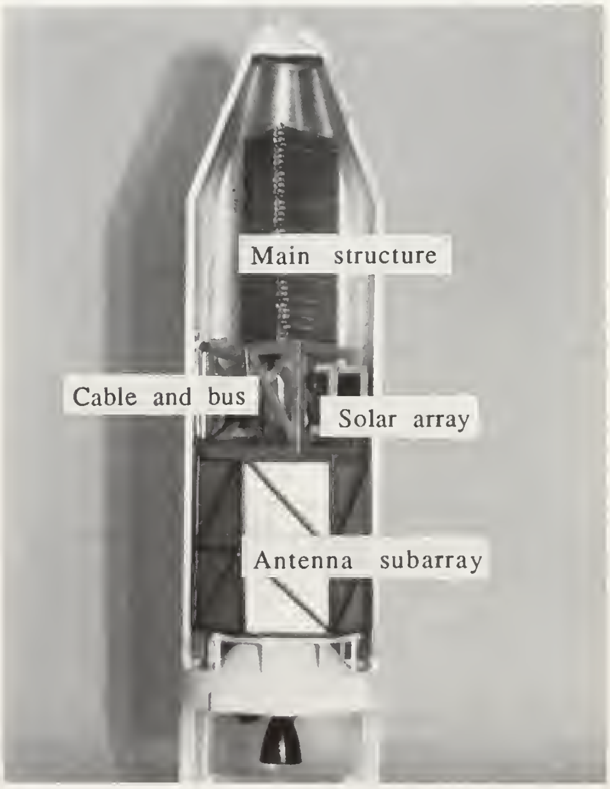

Fig. 3. A configuration of integrated payload in Ariane V nose fairing.

operated as a small SPS even if the width of microwave beams are not sharp enough due to smaller antenna size. An integrated payload configuration is shown by Fig. 3. Each unit is assembled in orbit and test operated and added to the unit(s) preceding in operation if it is a follow-on flight unit. Figure 4 shows a model of the flight unit assembled in orbit with the nose fairing on the same scale. There is a berthing space in the center of the first unit, where later flight units are unloaded. The construction work for additional modules will be made on the both ends of the prism to maintain the position of the center of gravity.

Fig. 4. A flight unit assembled in orbit.

Problem areas for further study

As a result of the system analysis, several points requiring to be scrutinized for further study have been identified as follows.

Technology options

As for energy conversion, solar cells are better fitted to this system than a solar dynamic system, considering the attitude control requirement. However, the assumed amorphous silicon solar cell has to be compared with others in terms of cost and mass properties and radiation degradation. The mass of the electrical cable which is larger than the structure mass is a critical problem for the sytem design. Further study on the possibility to use higher voltage, and analysis to shorten the length of the current path will be required.

Power transmission employing retrodirective as well as computer control is a key technology of this system in a LEO. The technology for this system is being developed with an engineering model as an experiment onboard the space station. The engineering data on the mass properties, thermal design, consistency of the high voltage of the power supply and other problems are not yet fully obtained. Selection of the type of semiconductor amplifier for the antenna elements will be most important from the standpoint of cost reduction and robustness of the system.

Many options can be considered for flight unit modularization. If the launch cost is higher than the payload system cost, the size and mass of a flight unit will be affected significantly by selection of the transportation system. This problem is related to the payload integration and orbital construction work. Automated deployment and assembly with robotics will be used for the orbital construction work. The optimum combination of these two functions should be pursued for the purpose of reducing the related cost.

Ground segment

Rectennas must be located in the relatively limited zone where the SPS is visible at an elevation angle of at least 60 degree. This is a zone between latitudes of 5.5 degreè north and south, or a 1200 km wide equatorial zone for an orbital altitude of 1000 km. Another constraint on site allocation is the minimum distance between two neighboring rectenna sites, which is required to make the power receiving time for each site as long as the beam angle can be controlled. Accordingly, the minimum distance between two rectennas should be 1200 km as well, and the reception time duration is approximately 3 minutes. Since the orbit altitude is nearly proportinal to the serviceable zone width of the latitude and the minimum distance between neighboring rectennas, a higher altitude covers more regions. On the other hand, the mass which can be carried by launch vehicle to a higher orbit will be reduced significantly. It will be necessary to compromise these two conflicting factors for orbit selection in addition to considering the debris condition.

Considering that the SPS 2000 system will be constructed modularly, the first few flight units will necessarily be used to test and verify the technologies of the system and operational

functions. One of the rectennas will be designed as an experimental rectenna station, where the characteristics of the power transmission system are measured and newly developed equipment and facilities will be tested. Some scientific observation facility such as a radar for high altitude atmospheric research will be useful for observation of the phenomena caused by the interaction of the microwave beam and the ionosphere below 1000 km.

The ground system can be used for small local electric power stations, which are now powered by small hydraulic generators, photovoltaic generators or diesel generators. In this case, the power system need not compete with a large electric system for economical superiority. High reliability and quality of electricity are not mandatory. In this respect, this model can be used for isolated customers at many different sites in developing nations in the equatorial zone.

To prepare for evolution of the system, some of the rectennas will be designed as a future key rectenna sites. It is desirable for such a station to be provided with growth capability of the rectenna size and a longer distance from neighbouring rectennas for higher orbit operation. Such a rectenna will be useful for testing the first flight unit, whose microwave beam width is three times larger than that of a complete unit, so that power transmission tests will be performed more effectively with a larger rectenna.

Various types of rectenna can be designed for SPS 2000 independently from the orbital segment. More detailed discussions by other authors are expected (7 and 8).

Evolution capability

This system will be flexible and evolutionary in several ways. Firstly, it can be operated while incomplete during construction as described. It will also be possible to increase the power output by adding extra flight modules. The technologies for this capability will be common to those required to maintain the orbital system. Accumulated experiences of the orbital operation will be valuable.

Secondly, multiple orbital power stations can be built and operated. A series of units in the same orbit could be coordinated to supply power for longer periods. This is the simplest way to increase electrical energy received at a rectenna without additional investment in the ground segment. If the orbital altitude is 1000 km, the maximum number of SPSs is thirty three and then all the rectennas can receive the nominal power from space almost constantly from early morning to early evening every day.

In the future, if advanced space technology such as electrodynamic plasma motor is available, it will be possible to move the SPS up to a higher orbit, which allows a rectenna to receive a larger portion of the electricity generated in an orbital period due to the longer visible time. Some coordination between rectennas will be necessary due to overlapping of the expanded operational area of each rectenna. Increase of the sizes of the transmitting antenna or rectennas will be required. If a rectenna diameter is 10 km as in the case of the Reference System, the present SPS 2000 can be operated approximately three times as high as the original orbital height.

The key technology developed for this system can be applied later to such larger systems as the Reference System. The rectennas for this early model can be designed to take more service from the more advanced system evolving from the smallest model. The quality of the electricity will be improved with adding energy storage systems to rectennas.

Features of the prospective project

The CDEP has indicated that even if an SPS is technically feasible, it is difficult to realize it as an actual project or program because of other reasons. To look into this aspect, I would like to list and briefly discuss the important features required for the 10 MW class SPS which is much smaller than the Reference System, and the possibility for SPS 2000 to be realized from these viewpoints.

Realistic demand research

A 10MW class SPS discussed here is equivalent to a 300 kW terrestrial electrical power plant in terms of the average daytime power supply. Although just an experimental facility in industrialized nations, it could be useful in remote land. We need to find out the demand to use such a system as an operational power generating system, to justify the investment. Without such a demand, the SPS will not be successfully demonstrated as a power system for terrestrial application. This approach and the simple system will make SPS 2000 significantly realistic, compared with the Reference System whose concept has been developed as a hypothetical national electrical power system.

Growth and technology update strategy

The first commercial electrical power station

made by Edison started service with a single 200 HP engine in 1882 (9). The present terrestrial electrical power systems have evolved gradually from the early age models, responding to the demands and incorporating the progress of technologies. The situation of SPS 2000 should be similar to the Edison's first power station. It will not be a planned step of technology development of a future system in a framework of a huge single program. Space projects well defined in advance according to phased project planning, often give new technologies little chance to be employed when available. Since the mission of SPS 2000 is to simply supply electrical power from space, and the system is modularized, technology updates which allows technologies used for major subsystems to be changed to avoid outdating of the system after it is planned can be applied more easily than the traditional sophisticated spacecraft. To ensure this, SPS 2000 definition of detail will be made only for each flight unit, but not for the overall system.

Low cost policy

The cost estimation of the Reference System suggested that the SPS electrical power would be economically competitive with conventional power systems. However, the estimation is based on a low cost transportation system specially developed for this purpose. In the space industrialization era, the transportation service should be provided by the space infrastructure. Therefore, SPS 2000 project will use available commercial transportation systems. The present transportation price is very expensive. The approach taken by the communications industry to make space business pay off the high price is to increase the performance of a space system per flight by employing expensive high technologies. This approach can not be applied for a power system which can not enjoy the value added economy. The only way to reduce the cost is to reduce the cost of the orbital and ground facilities. One definite cost target of the orbital system of SPS 2000 is terrestrial solar power systems. Assuming the cost is 10 US\$/W, the approximate figure for 10 MW model is 100 MUS\$. In this case, the launch cost dominates the payload cost, so that future reduction of the transportation cost will directly enhance the merit of the SPS system. In other words, success of the first SPS will benefit the future of space transportation.in return.

Public acceptance

The radiation hazard caused by the transmitting microwave is a major public concern about SPS. The hazard is not known well but exaggerated and often misunderstood. A low power model like SPS 2000 would be comparable with a conventional radar system in terms of the radio power level. A rough estimation of the power level is given for SPS 2000 here. When the diameter of the transmitting antenna is 100 m and its distance from a rectenna is 1100 km, the rectenna diameter is 3 km. The radiation hazard of microwave of SPS 2000 which generate 10 MW will be roughly evaluated by comparison with the 5 GW Reference System having a 10 km diameter rectenna: the microwave power density for SPS 2000 is calculated to be forty five times smaller than that of the Reference System. The actual power level is about 0.5 mW per square centimeter at the beam center reaching to a rectenna.. Considering also the exposure time of a few minutes in an orbital period of about 100 minutes, the hazard can be evaluated in advance by accelerated experiments. Therefore, the radiation hazard will not be a major obstacle to the start of this project. On-site experiments on hazards evaluation can therefore be conducted safely, and experimental data will be obtained for later projects.

International feature

An SPS to be placed in a low earth orbit inevitably provides many nations with an opportunity to participate in the project, while an SPS in the geostationary orbit can be used exclusively by the owner country. Especially, in the case of SPS 2000, the benefits of the SPS system can be shared by the countries located in the equatorial zone. Thus the project can be planned in the context of international cooperation between industrialized and developing nations. The international community has the opportunity to do something constructive for the future, based on the technologies developed in the twentieth century, which were mostly used for military purposes. SPS 2000 is not large enough for such a purpose but may work as the initiator of this kind of cooperative enterprise.

Conclusions

ISAS solar power satellite working group has developed a preliminary concept of a 10 MW class SPS strawman model. In terms of the principle and key technologies, the model is in accordance with the Glaser's original concept and the Reference System of the CDEP. However, the size and the purpose are different from theirs, since the study aims at demonstration of electric power supply to customers at earliest opportunity, while the Reference System was designed as a future national electric power system of the industrialized country.

To solve the problem of extremely high cost of space systems which is considered as the main obstacle against this purpose, the following points have been emphasized for the conceptual design.

1. To simplify the orbital segment, the solar array and antenna are fixed on the same structure to be stabilized by gravity gradient force.

2. To make the concept realistic, only existing technologies, including those yet to be qualified, will be used, although renewal of technologies will be considered positively.

3. To reduce the cost for transportation to space which is dominant portion of the total project cost, the equatorial low earth orbit has been chosen rather than the geosynchronous orbit.

As a result, a concept of a model designated as SPS 2000 is being developed. SPS 2000 is modularized by flight units to be carried by a commercial launch vehicle. Every subsystem is divided into equal portions and installed evenly in each module of flight units. Thus, each unit can be operated and tested as a small SPS, although the performance is not satisfactory for customer service. SPS 2000 will transmit the microwave power to rectennas located along the equator separated from each other by distance of 1200 km for about three minutes in every orbit path.

Unique features of an SPS project indicated by this cenceptual study will be summarized in comparison with the Reference System, as follows:

1. SPS 2000 is an evolutionary system which can be started from a size of a payload of a launch vehicle. It can be a first milestone even for the Reference System

2. SPS 2000 is substantially international system. International aspects of SPS will be discussed more seriously for SPS 2000 than for the Reference System.

3. SPS 2000 can serve exclusively the equatorial zone, especially benefiting geographically isolated lands. This will be a new aspect of societal issues which was not discussed in the CDEP.

These features suggest that the potential customers as well as electric utilities will play an important role in the next stage of the study. Their participation in the further study on the aspects of technology options, ground segment design and possibility of future evolution will be an essential step for SPS to be evaluated correctly without prejudice.

Acknowledgements

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B1.5 Design considerations for the "SPS 2000" ground segment

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Abstract

The construction of a near-term solar power satellite (SPS) has been proposed, in the form of a satellite in equatorial low Earth orbit transmitting up to 10 MW of radio-frequency (rf) power at 2.45 GHz, with the objective of demonstrating the generation of useful electric power on Earth using available space technologies and launch services. This paper examines the main factors that must be considered in the design of the ground segment (ie the rectennas and related power-conditioning equipment) for such a system, which will become important research facilities, of interest to electric utilities in every country.

Résumé

La construction d'un petit Satellite Solaire de Puissance (SPS) a été proposée, sous la forme d'un satellite en orbite équatoriale basse transmettant jusqu'à 10 mégawatts de puissance radioélectrique à 2,45 GHz. L'objectif est de démontrer la génération de puissance utile sur Terre en utilisant les technologies spatiales et les services de lancement disponibles actuellement. Cet article examine les principaux facteurs à considérer dans la conception du secteur terrien - les rectennas et le conditionnement de puissance associé - d'un tel système de démonstration qui constituera un pôle de recherches intéressant pour les distributeurs d'électricité de chaque pays.

1. Introduction

The views of potential customers of the SPS project are very important in the decision on how to proceed. The customers for the SPS will be the electric utilities of the world. In general, electric utilities are large companies with strong finances, based on their large, high quality cash flows and with extensive technological skills centred on electrical engineering. If electric utilities became convinced that SPSs offered a profitable source of electric power, they could more or less finance their development. The initial priority for SPS research should therefore be to interest the electric utilities, and progressively to convince them that SPSs could be a commercially competitive source of electric power.

However, electric utilities do not have space engineering expertise, and it is not likely that they will develop such expertise - a task which would be very expensive and of uncertain benefit. From this viewpoint, most SPS-related experiments that have been proposed by the space industry, such as generation and transmission of microwave power between satellites in orbit, are of little interest to utilities. They cannot use them; they cannot assess them technologically; and they cannot draw any useful conclusions from them about the likely future cost of SPS power.

By contrast, it would be of considerable interest to utilities to demonstrate the transmission of power from an orbiting satellite to a rectenna on the ground. Consequently the objective of the proposed "SPS 2000"

project (1) is to demonstrate the generation of useful electric power on Earth from a microwave beam transmitted from an orbiting solar power satellite, using available space technologies and launch services. The "SPS 2000" project has a number of key design features which have major implications for the design of the ground segment.

2. "SPS 2000" Key Design Features

a. Equatorial Orbit
The space segment is to operate in an equatorial orbit, in order to provide rectennas with more frequent deliveries of power.

b. LEO satellite
The satellite will operate in LEO, approximately 1000 km altitude, in order to reduce launch costs, and to minimize the size of the transmitting antenna required.

c. 3 km diameter microwave beam "footprint"
The microwave power transmission system (MPTS) will be sized to deliver power within a "footprint" some 3km in diameter (North-South) when the transmitting antenna is 100 m in diameter.

d. Power output from 1MW to 10 MW
The space segment will have a power generation capacity of approximately 1 MW(rf) initially and will be expanded to as much as 10 MW(rf).

e. Space segment to be upgraded
The space segment will be upgraded progressively in order to increase the value of the energy delivered to each rectenna.

The operation of the SPS 2000 system would generate both electric power and information about the system's operating characteristics. This raises interesting questions about the optimum balance between these two objectives. Although the provision of commercially competitive electric power is not the initial objective of the "SPS 2000" project, this is the ultimate objective. Consequently economic considerations are important in the design of the ground segment, and will be of particular interest to electric utilities.

3. Implications for Ground Segment Design

3a. Equatorial orbit

The main implication of the selection of an equatorial orbit for the SPS 2000 space segment is that all the rectenna sites will be on or near to the equator. The maximum distance from the equator that would be possible will depend on the design of the MPTS, in particular the microwave beam steering capability. It is planned that the transmitting antenna will point to the Earth's centre and the microwave beam will be electronically steered to an angle of 30 degrees to the vertical, which will limit the siting of rectennas to within a few hundred kilometres of the equator itself. However, as the latitude of the rectenna increases, the duration of power transmission from the satellite decreases, reaching zero at about 600 km from the equator.

The countries in which rectennas could in principle be sited are any or all of the following: Ecuador, Colombia, Brazil, Gabon, Congo, Zaire, Uganda, Kenya, Somalia, Indonesia, and some Pacific islands. It is noteworthy that none of these countries is a major industrialised country, and that their equatorial regions are mostly low-income, agricultural areas where electricity is not readily available. One or more of these countries could obtain major benefits from playing an important role in the development of the SPS.

To the extent that the rectennas were seen as valuable facilities, economically, scientifically and/or politically, there might be many candidate nations. For producing maximum engineering information it would be desirable for several rectennas to be built and operated. This creates the possibility of significant economies of scale and

learning through mass production; of political momentum through international collaboration; and of United Nations support for a project of interest to both industrialised and industrialising countries.

3b. LEO satellite

The selection of an altitude of approximately 1000 km entails that transmission of power to a rectenna will be of quite short duration, some 200 seconds continuously if the microwave beam can be steered up +/- 30 degrees to the vertical. It also entails that the angular direction of the microwave beam will be changing quite rapidly, approximately 0.3 degrees/second.

In order to simplify the initial SPS design it is not planned to transmit power during the local night-time, which would require on-board power storage. Consequently for a 1000 km circular orbit there would be some 8 transmission periods/day to each rectenna, giving approximately 1600 seconds total power delivery per day.

A wide range of experiments will be possible using the ground station (2). These will include tests of the system's steady-state operating characteristics under different conditions, and tests of its response to the range of transients to which it will be subject - start-up, shut-down, load-following, unplanned outages, and so on. Extended tests will also be possible on the system's reliability, and on its side-effects such as electromagnetic interference under different conditions.

For users of the power delivered by the SPS 2000 ground segment, continuous electric power will be more valuable than short bursts of power, and so from the point of view of power generation, it will be desirable for the rectenna system to include some energy storage capacity. Such a system would be required to absorb energy for about 200 seconds and discharge for about 2 hours. Thus, for example, if a rectenna generated 100 kW(E), it could store (100 E/18) kWhr, and deliver approximately (100E/18x2) kW continuously, where E is the efficiency of the electrical storage-discharge cycle - perhaps 2 kW(e) continuously with an efficiency of the storage cycle of 72%. On the same assumptions, 1 MW(e) from the rectenna could produce 20 kW(e) continuously. Today, commercially available batteries cannot be charged as fast as this. Consequently alternative energy storage technologies, such as water pumping would be necessary. However, as the space segment is upgraded, the performance required of the storage system is reduced (see 3e below).

In general, average rectenna power output will be

(P.T.Y.E.N/24) kW(e), where

P(kW rf) is the rf power transmitted to the rectenna,

T(hrs) is the length of continuous power delivery to the rectenna,

Y is the efficiency of rf-DC power conversion at the rectenna, and

N is the daily number of satellite passes in daylight.

The initial design is intended to minimize the development cost of the space segment, which is much more expensive than the ground segment. Subsequently, in order to reduce the cost of electricity produced, it will be desirable to perform a trade-off between many factors, both technical and economic.

3c. Microwave beam "footprint"

A nominal SPS 2000 unit with 100 m diameter antenna can focus the beam within a diameter of 3 km on the ground. For an equatorial rectenna, the microwave beam terrestrial "footprint" of 3 km diameter determines the minimum area of 7 sq km. During the period of power transmission the area illuminated by the main lobe of the beam will start as an East-West ellipse with major

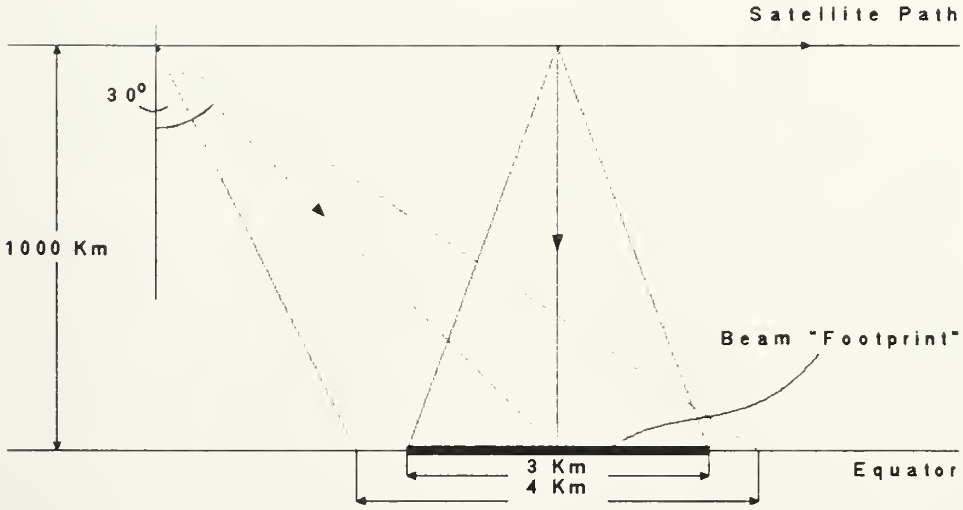
axis of 4 km, shrink to a circle of 3 km diameter, and increase to an East-West ellipse again, the maximum East-West diameter being determined by the maximum angle of inclination that is feasible (see Figure 1).

charge. This would require the rectenna to cost approximately 1Yen / sq m (see below).

The objective of operating the SPS 2000 rectennas is not only to generate electricity,

Figure 1

Microwave beam footprint variation during pass.



Not to Scale

For an initial beam power of 1 MW(rf), the average power density would be only 141 mW/sq m, which is less than 0.1% of that in the DOE SPS Reference System. The actual power density at different points of the rectenna will depend on the microwave beam power density profile, and will influence the optimum size of the rectenna.

For a commercial SPS system, the size of a rectenna is determined by economic considerations: The amount and hence the value of power received per sq m of rectenna surface decreases with distance from the centre of the beam. The edge of the rectenna is where the cost per sq m of the rectenna is equal to the present value of the energy that the rectenna will produce per sq m over its lifetime, less the cost of microwave supply.

With an average requirement of approximately 7,000 sq m / kW(rf), and so of approximately 350,000 sq m / kW(e) continuous, the ground system is clearly not cost-effective in commercial terms, even if the microwave power is delivered without

but also to generate information. Nevertheless, it may be that the optimum rectenna size would be considerably less than the overall beam footprint (see 3.e below).

From 3b, the continuous rectenna power will be

(P.T.Y.E.N/24) kW(e).

If the value of 1 kWhr is V Yen, the annual electricity revenue would be
(P.T.Y.E.N/24)8760.V Yen,

that is (365. P.T.Y.E.N.V) Yen.

The present value of the lifetime revenue is therefore:

(365 . P.T.Y.E.N.V.D) Yen,

where D is given by $((1+i)^n - 1)/i(1 + i)^n$, where i is the interest rate, and n is the operating lifetime. The limiting value for this (when the lifetime is indefinite) is 1/i.

Typical values for the variables might be: P = 1000,

T = 1/18, Y = 0.5, E = 0.8, N = 8, V = 10, D = 5. These give a value of 3.2 million Yen or approximately 0.5 Yen/sq m.

The central portion of a rectenna would have a power density perhaps 10 times this average, giving perhaps 5 Yen per sq m. Even at this level of revenue the rectenna would not be commercial. It seems possible that even for demonstration purposes, only the central portion of the microwave beam footprint would be collected. The practical cut-off point would depend on many factors, but might be as little as 0.5 km from the beam centre. Because the satellite would be travelling from West to East, the effective East-West extension of the rectenna would need to be increased if all the power available were to be collected. However, the economic value of the outer regions of an East-West ellipse would be even less than the value of the central circle due to the even shorter period of power delivery

3d Power output from 1MW to 10MW

Once a first 1 MW sub-unit of the "SPS 2000" space segment is operating, it is proposed to upgrade it progressively by adding more 1 MW sub-units up to a maximum of 10 MW(1). Increasing power output in this way would provide further experience of system design and operation, and would also reduce the cost of power produced: For a given rectenna cost, the cost per unit of electric power produced would be inversely proportional to the rf power delivered to the rectenna.

NB the intensity of the microwave radiation outside the central section, even for 10 MW(rf) transmission, would lie within existing public exposure limits.

3e Space Segment to be Upgraded

The space segment could be upgraded in other ways:

1. Power could continue to be delivered in short bursts, but more frequently, by siting more satellites in the same orbit. Ten satellites spaced evenly around the orbit would require only nine minutes' storage capacity at the rectenna to provide continuous power. Such satellites need not be produced by a single organisation; a number of different groups might use different designs, thereby introducing an element of competition.

2. Alternatively, longer periods of continuous power could be delivered by formation flight of multiple satellites close together in the same orbit, and coordination of their power transmission to rectennas. For example, ten satellites would provide 30 minutes power every two hours, requiring 1 1/2 hours' storage capacity in order to provide continuous power to each rectenna.

3. The periods of power delivery could be lengthened by increasing the satellite altitude. This would reduce the number of rectennas that could each receive the maximum-duration power from a single satellite, the extreme case being the 1:1 GEO satellites of the US Reference System.

Raising the altitude also increases the distance North and South of the equator to which the satellites could deliver power. In addition, raising the altitude increases the area required of the

satellite transmitting antenna and/or of the rectenna. In order to reduce the cost of power it is then necessary to increase the satellite power output, as proposed, for instance, in the Energy Storable Orbital Power Station (ESOPS) with an output of 70MW, and transmitting antenna diameter of 200m(3).

4. The periods of power delivery could be extended through the night by using energy storage on the satellites. For example the ESOPS proposal includes 45 minutes thermal storage capacity, permitting power delivery on every satellite pass (3). The optimum allocation of storage capacity between the ground and space segments will depend on many factors, including economic considerations.

5. The rf beam parameters (including power density profile and wavelength) could be altered to achieve an improved power distribution pattern at the ground. The first SPS 2000 space segment is designed for minimum development cost, but later units might be used to evaluate different antenna systems.

6. The power delivered could be increased by delivering power to a rectenna from two satellites close together in the same orbit simultaneously, as proposed in (4). If this possibility is feasible in practice it would greatly increase the potential value of a rectenna to an electric utility, by reducing the capital cost per KW of capacity by 25-33% (5). It would thereby increase the price that utilities could offer to satellite operators for supplies of rf power. The SPS 2000 system would enable exhaustive experiments to be performed.

These possible developments all lead towards the final objective of delivering continuous, high-density rf power, and all have implications for the design of the ground segment. In particular, if such changes were planned to occur within approximately 5 years of the initial operation of the system, it would probably be economic to design the ground system initially to accommodate them. For example, if the power density in the microwave beam was to be increased, it would be appropriate for the rectenna to have a higher power capacity than if this change was not planned, even at the cost of having lower rf-DC efficiency initially.

The power storage and related systems could be altered fairly easily at a later stage, being discrete systems at the edge of the rectenna. However, the rectenna itself, covering some millions of sq m, would be less easy to upgrade. The detailed design of the rectenna surface electronic circuitry is very dependent on the planned power density. Consequently if this was to be increased by several hundred percent, this would have a major effect on the optimum design.

It would, nevertheless, be possible to design a rectenna for ease of upgrading. For example, if made easily movable like a lightweight mesh, the panels might initially have power handling capacity in inverse proportion to their distance from the centre of the rectenna. Then, in order to upgrade the rectenna, all panels would be moved radially outwards and reconnected appropriately, and new, higher-capacity panels would be sited in the centre.

4. Rectenna System Detailed Design Considerations

The minimum cost rectenna would consist of a single flexible layer in the form of an open mesh that could be installed simply by unrolling long sheets and interconnecting them appropriately. The mesh could consist of 2mm diameter plastic cable carrying rf-DC printed circuits and covered with a protective layer. Such an open mesh would pass rain and sunlight, but it would have an efficiency of only perhaps 10% since the efficiency of rectenna power reception is very dependent on the presence of a reflector plane (see Figure 2).

These two designs could be installed relatively easily even on unprepared land, thereby causing minimal environmental disruption. For some purposes however, a more expensive, maximum-efficiency rectenna design would be preferable, such as the circular microstrip antenna devised by Itoh et al(6).

In the DOE SPS Reference System design high rectenna efficiency was achieved by interconnecting many rf dipoles and using high-power diodes with high efficiencies. This approach increases the directional sensitivity of the rectenna.

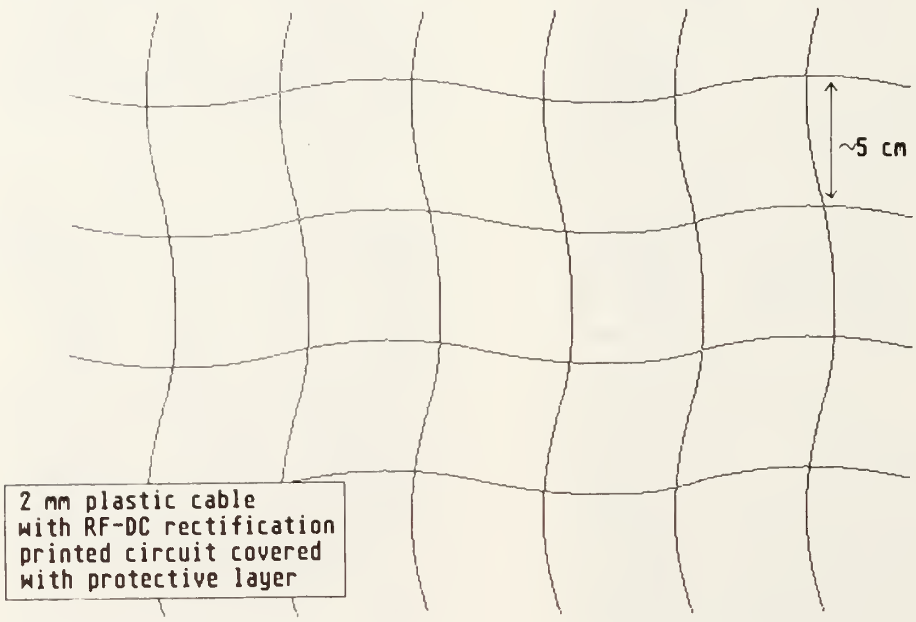


Figure 2
Hatsuden mahoh no jutan, or "electricity generating magic carpet".

A simple reflector plane could be added to such a mesh by attaching a metallised open plastic framework behind the active power reception plane. This would increase the mass by some 200%, and the cost by perhaps 100% (being much simpler than the front surface), but would increase the bulk for transport and deployment by perhaps 1000%. The efficiency would be increased to perhaps 50% (see Figure 3).

In order for the "SPS 2000" rectenna to receive power efficiently from 30 degrees East and West of the vertical, it will be necessary for series connections between dipoles to be mainly in the North-South direction, making the directionality of the rectenna greater in the North-South direction. The rectenna design proposed by Itoh et al(6) has the capacity to receive power efficiently from a wide range of East-West directions.

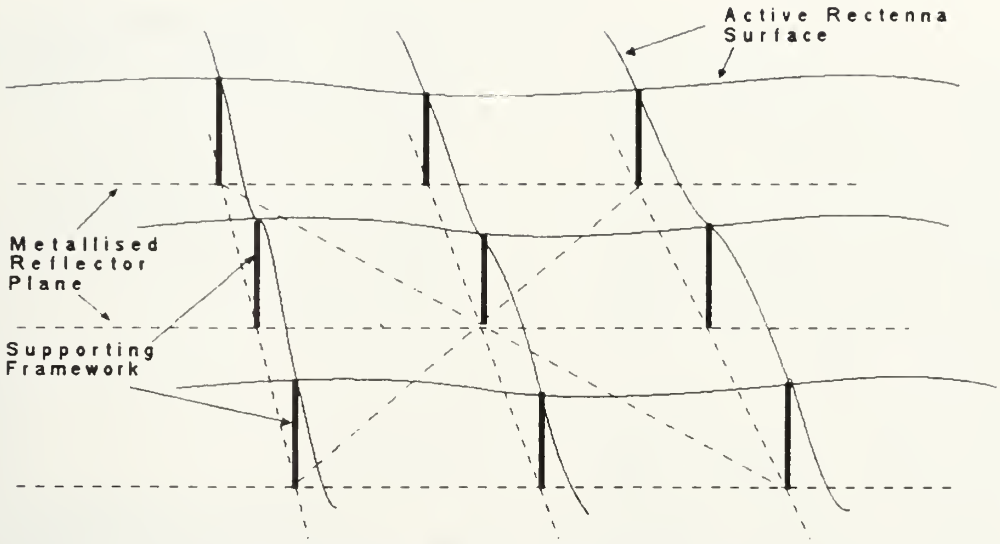


Figure 3: Low Cost Rectenna with Reflector Plane

For any given rectenna site there is a broad choice between a low-cost but low-efficiency approach and a high-efficiency but high-cost approach. The former would demonstrate the generation of some power at the lowest total cost; the latter would produce the most power and the most information for development purposes.

The optimum approach in any case would depend on the objectives of those financing the project. Economies of scale would be maximised by building and operating several similar rectenna systems; engineering experience would be maximised by using several different designs. A possible compromise would be to design two "standard" rectenna systems, at least initially:

Type A rectennas would be designed with the intention of being upgraded progressively to become large and stable sources of commercial electricity generated by a future geostationary SPS system. They would therefore have high efficiency and high power handling capacity.

Type B rectennas would be designed to remain local sources of relatively low power, with energy storage systems, at minimum cost. The "hatsuden mahoh no jutan" described above would clearly cost much less than a rigid structure.

In addition to either of these approaches, engineering research will require the installation of numerous sensors, data collection equipment and control systems, in order that utilities should be able to assess the potential of the SPS to the greatest extent possible. Such research would be valuable with both Type A and Type B rectennas. The potential scope of this research is discussed in (2). In brief, the SPS 2000 ground segment, and the experiments that it makes possible, have the potential to resolve essentially all of the concerns on which electric utilities must be satisfied before they can offer a price to satellite operators for supplies of microwave power from space.

5. Conclusions

It is clear that many factors will have to be taken into account in the design of the SPS 2000 ground segment. Although SPS 2000 rectennas will initially be more valuable as sources of engineering data than as sources of electric power, they will nevertheless have the potential to earn commercial revenues from the sale of electric power from an early stage.

The research for which the rectennas will be used will be both technical and economic. That is, while technical results such as determining the rectenna design with the highest efficiency will be important, ultimately it will be the most cost-effective design, that is the design giving the minimum cost per kilowatt-hour delivered, which will be preferred by utilities. Consequently, not only the technical results of experiments performed with different ground system and sub-system designs will be of interest, but also the costs of these different experiments.

Following the comprehensive programme of experiments that will be possible with the SPS 2000 ground segment, electric utilities will be in a position to estimate reasonably accurately the cost of constructing a rectenna to a given specification, its operating costs, and the cost of integrating its output with their distribution grids. This will enable utilities to calculate the price which they would be prepared to pay potential satellite operators for supplies of microwave power to a given specification.

The ground stations of the SPS 2000 project will be very important research facilities, being of unique interest to electric utilities in every country. Ultimately, as the space segments are upgraded to provide continuous, high-density rf power, the ground segments will become major sources of electricity. The SPS 2000 project therefore offers the equatorial countries the opportunity to play an important role in the development of the SPS, which promises to become a major, non-polluting energy source for the world.

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B2.1 The global solar energy concept "1 MW Demonstration Mission"

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It is imperative - and highly recognized in the industrialized world - that an essential and cumulative part of the global energy demand must be contributed from regenerative sources from now.

The Global Solar Energy Concept (GSEK) is a synonym for an initiative to join the efforts of the terrestrial and orbital solar power votaries in a convincing and effective "phased approach".

Step 1 : Start instantaneously with fully operational, large-scale solar power plants on Earth. Cross-check recurrently the adaptability to the necessities of Step 2.

Step 2 : The moment the technologies are mature, this option will be highly attractive for economy - use the space offer at industrial scale by high-efficiency solar energy transformers, radiate energy to ground around the clock, use the existing (adapted) terrestrial power plants and infrastructure as the ground segment (cf. Fig. 1).

More details of the philosophy behind and the various benefits of this approach will be outlined in the full paper.

Two principal benefits are obvious :

- The opportunity to have solar energy from the start
- The opportunity to decide when to go to orbit - with mature technology and investors confident of success.

Now, in order to pursue a phased in-time realization of the orbital-terrestrial compound, the development of the necessary technologies (particularly for the orbital segment) have to be full-scale initiated. Additionally, a program has to be staged to "timeline" the required technology experiments and in-orbit demonstrations.

One key element to do this is the 1 MW demonstration station (Fig. 2). The ultimate goal of the demonstration is the :

- Verification of the design data
- Proof of technology and performance
- Proof of biological and ecological compatibility
- Identification of problems and limitations
- Identification of requirements and improvements
- Promotion of confidence, political and social acceptance
- Promotion of the willingness to invest

A survey of the demonstration station will be given, including configuration, design features, main subsystems, performances, masses, orbital installation and operations, and demonstration program.

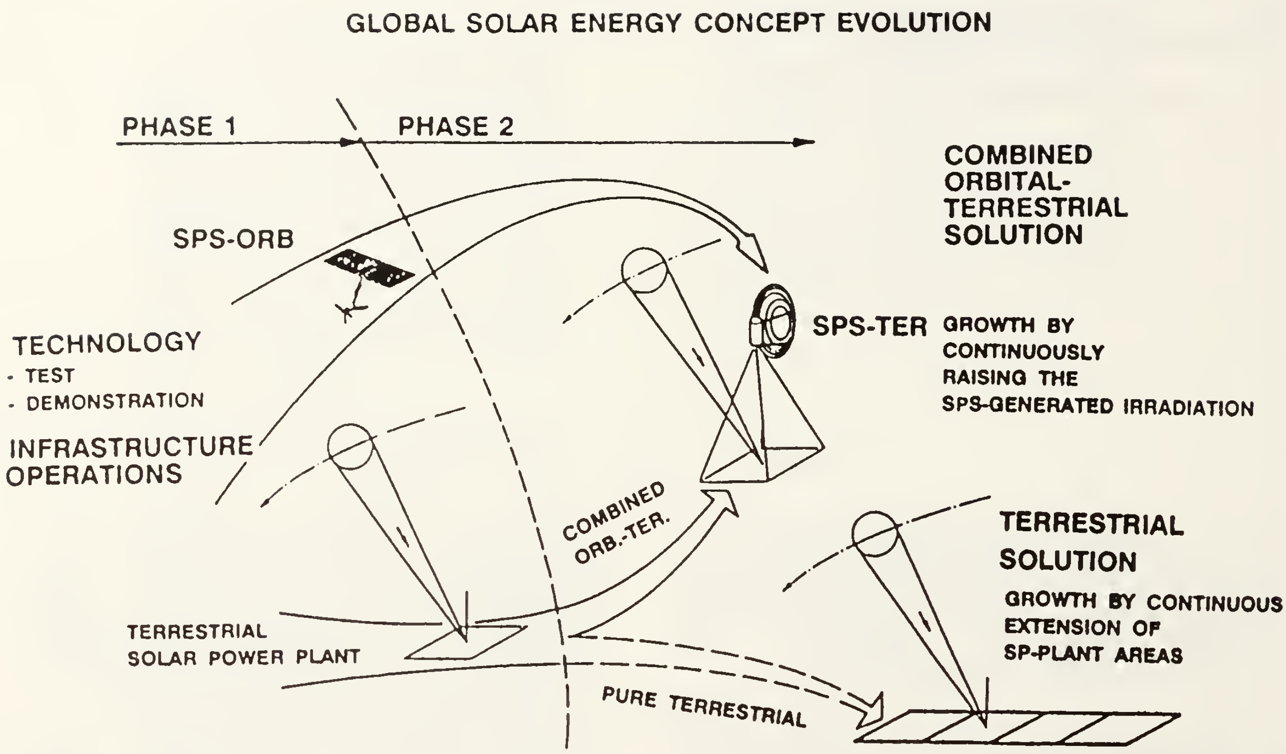

Fig. 1: The Global Solar Energy Concept
"Concept Evolution"

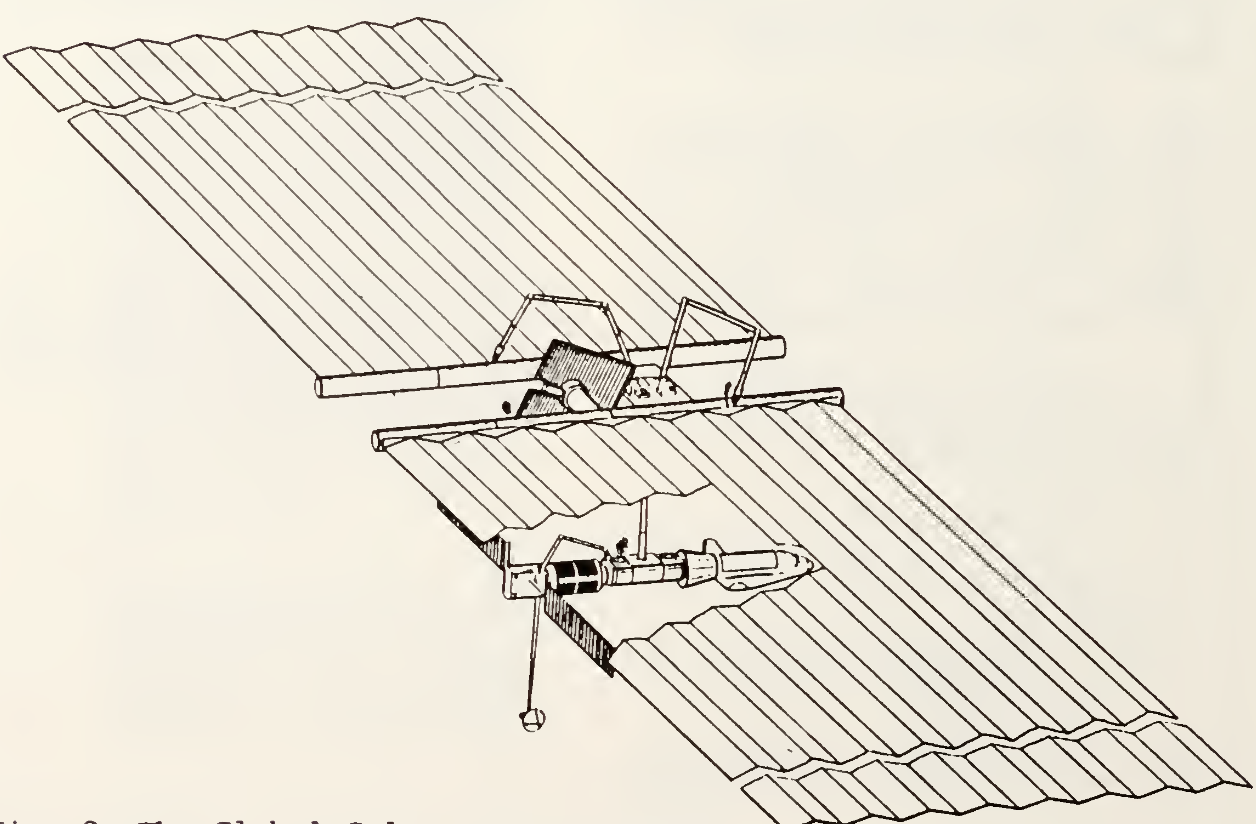

Fig. 2: The Global Solar Energy Concept
"1 MW Demonstration Station"

B2.2 A feasibility study of Power Supplying Satellite (PSS)

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Abstract

A feasibility study is given on a new type of an orbiting power station which supplies a power of the order of 100kw to orbiting customers (satellites or space stations). We call the orbiting power station "PSS" which stands for Power Supplying Satellite. The PSS is composed of three main parts; a power generator, a power transmitter and a satellite bus system. The unique feature of the proposed PSS is the usage of a module which has a solar-cell array on one side and a microwave transmitting antenna array driven by FET-amplifiers on the other side. These autonomous transmitter modules are used to form a large disc-structured active phased array of 40m diameter which transmits a 100kw energy beam of 24GHz microwave.

The frequency of 24GHz is chosen to reduce the size and volume of the transmitting antenna. DC electric power generated by the solar cells on the top plane of the module is fed directly to the semi-conductor FET amplifiers located under the solar-cells, converted to 24GHz microwave, and then transmitted from the antenna arrays on the bottom plane of the module. These autonomous solar-cell-transmitter modules make it possible to eliminate the rotary joint and the DC power collecting network from the design of the PSS and SPS system.

The PSS provides the following advantages; (1) availability of high power electricity to orbiting customer satellites or stations; (2) reduction of weight and volume of power system on customer space vehicles; and (3) technical go-forward for the future SPS.

Résumé

Une étude de faisabilité est présentée concernant un nouveau type de station orbitale de puissance, fournissant une puissance de l'ordre de 100 KW à des satellites clients ou à des stations spatiales.

Nous nomons la station orbitale de puissance "PSS", acronyme signifiant Power Supplying Satellite. Le PSS est constitué de trois parties principales; un génerateur de puissance, un émetteur de puissance et un système de contrôle. La caractéristique unique du PSS est l'utilisation d'un module ayant un ensemble de cel-

lules solaires d'un côté, et un ensemble d'antennes alimentée par des amplificateurs FET de l'autre côté. Les modules forment une grand ensemble plan d'antennes à phase controlée de 40 m de diamêtre, émettant un faisceau micro-onde de 24 GHz, de puissance 100 KW.

La fréquence de 24 GHz a été choisie afin de réduire la dimension et le volume des antennes d'émission. Le cou rant continu généré par les cellules solaires sur le pont supérieur alimente directement les amplificateurs à semi-conducteur FET sous les cellules solaires, et est convertit en micro-onde de 24 GHz, qui est ensuite émise par le groupe d'antennes situées sur le pont inférieur. Ces modules joints cellules solaires-emetteur rendent possible l'élimination d'un joint de rotation ainsi que du réseau distribuant la puissance du courrant continu.

Le PSS a les advantages suivants; (1) mise à disposition d'une grande puissance électrique pour des satellites en orbite clients ou pour des stations spatiales; (2) réduction de poids et de volume des systèmes d'alimentation des engins spatiaux clients; et (3) avancée technique pour le future SPS.

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1 Introduction

The man's prosperity has been possible by expansion of four quantities; the area of habitation, materials and food, population, and energy. It is obvious that all of the four quantities will eventually (but not in the far future) reach their limit of availability and thereby choke the future of mankind. From this point of view, space civilization is inevitable in the 21st century to guarantee ever-increasing activities of mankind.

The Solar Power Station (SPS) proposed by P. Glaser in 1968 was originally supposed to become a rescue for the lack of electric power demand on our mother planet without destroying the Earth's environment[1]. This idea is still valuable and should be realized before the world economy collapses due to the crisis of oils which will become shortly unavailable by the middle of the next century. However the SPS is only a milestone of the space civilization program. Not only the demand of power on the Earth but that in space will have to be satisfied by Space Power Facilities. The SPS, which is planned to be placed on the Geostationary Orbit, is not always suitable for power transmission to fast-orbiting space vehicles. A different design for such need must be studied other than those having been made for the SPS.

The present paper presents a feasibility study of a Power Supplying Satellite (PSS) and proposes some new concept of design of the PSS.

2 Concept of the PSS

The PSS is an orbiting power satellite with a capability of feeding a maximum power of 100kw to orbiting customer satellites or stations. A schematic illustration of the PSS is given in Fig. 1. It uses a 24GHz microwave as an energy carrier in contrast to 2.45GHz proposed for the SPS. The reason for this is that the higher frequency reduces the size of the transmitting antennas and hence the volume and weight of the PSS. Regardless of this merit of using higher fre-

quency of 24 GHz, the SPS is supposed to use 2.45 GHz microwave to avoid a strong absorption and damping by the Earth's atmosphere. However, in case of the PSS, the power transmission is limited only in space and thus is free from the problem of power absorption by the water molecules.

The advantages of the establishment of the PSS as one of the space infrastructures are as follows.

(1) A High Power Availability in Space

Power in space is normally generated by deployed paddles of solar-cell array. However, a high power supply by the huge solar battery system requires more complicated control system and enhances the weight and volume of the necessary solar paddles. Therefore the attitude control of the heavy solar paddles produces the peiturbation of an artificial gravity in the spacecraft, which destroys the ideal zero-gravity environment for some material science and processing in space. Such bulky and complicated onboard power systems of the spacecraft could well be avoided by replacing the solar cell paddles with much lighter and simpler microwave rectenna system. The PSS is capable of feeding power up to 100 kw to such rectenna-equipped customer satellites or stations.

(2) Establishment of Key Technology of Microwave Energy Transmission

Though the frequency of the microwave used for the SPS is an order of magnitude lower than the PSS microwave, most of the technologies developed for the PSS are transferable to the

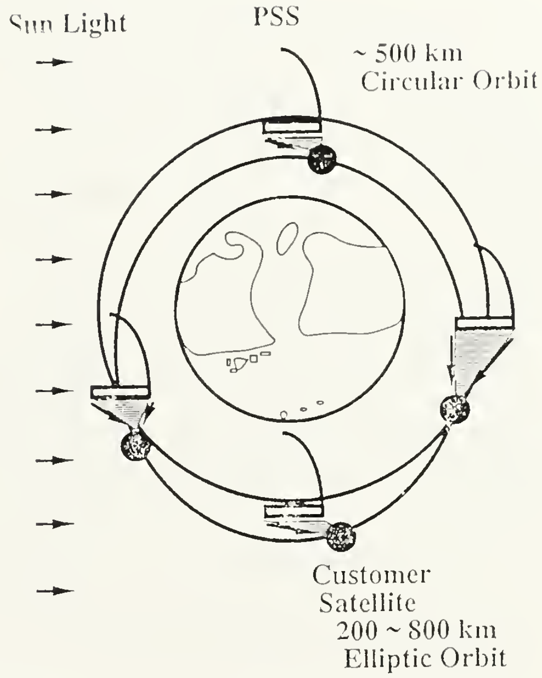


Fig. 1 A schematic illustration of the PSS concept.

future SPS. One of the new technological aspects of the PSS is the development of a unified module of power generator and power transmitter. The module, which we may call "autonomous transmitter module", consists of three layers; high efficiency solar cells on one side; transmitting antenna arrays on the other side; and F-class FET power amplifiers in between the solar cell and the antenna planes. The direct connection of the DC output of the solar cells to the FET amplifier of each active antenna element makes it possible to design much simpler structure not only of the PSS but also of the future SPS. In the SPS Reference System studied by NASA/DOE in 1980[2], DC electric power generated by the solar cells must be collected by a DC power collecting network in the huge SPS solar paddle. A critical technology of using super-conductor network for the current

collection is being considered for the SPS. This DC power collection network is not necessary for the proposed PSS. If this technology is once established then the design of the future SPS would become much simpler and less expensive. Another critical technological problem raised in the SPS Reference System is a mechanical rotary joint which electrically connects the differentially rotating Solar Paddle and the microwave transmitting antenna in vacuum. This is one of the difficult technological point of the SPS. However, the present PSS does not need such a rotary joint because the DC electric power is directly fed to the FET amplifier situating below the Solar Battery Unit.

3 Elements of PSS

The PSS is composed of three main subsystem; a power generator system; a microwave amplifier and transmitter system; and a satellite bus system. A schematic illustration of the PSS structure is given in Fig.2. The PSS is a disc-shaped satellite with a large disc with a diameter of 40m. The disc is composed of the autonomous microwave transmitter modules. The PSS is folded at the time of the launch as indicated in Fig.2 and is deployed in space. One side of the disc is the solar-cell array and the other side is the microwave transmitter. The solar-cell side should be controlled to direct to the sun. This sun-oriented attitude control naturally limits the direction of the microwave beam, even though the beam can be steered in a fairly wide angles by the active phase array. To increase the scanning range of the beam, we propose, as an option, to attach a reflector of sun light over the solar-cell array surface.

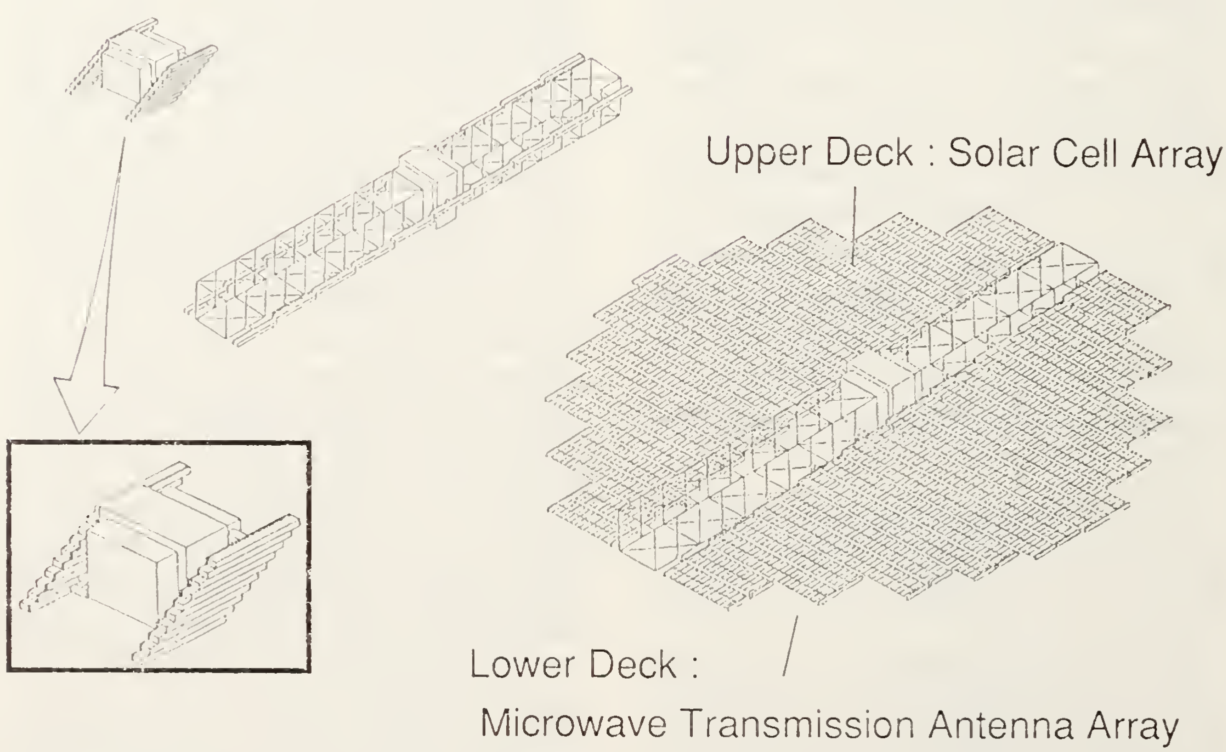


Fig. 2 Structure of the PSS

3.1 Autonomous Microwave Transmitter Module

A block diagram of the Transmitter Module is shown in Fig.3. The FET power amplifiers are power-supplied by the DC input from the solar-cells and generate 24GHz microwave. A new scheme retrodirective phase control system is used for the beam control. A pilot signal of one third of the transmitting frequency is used. This simple conjugate phase generator can determine the phase of the transmitted microwave with no phase ambiguity because only multipliers are used and no dividers are used in the circuit.

3.2 Transmitting Antennas and Rectennas

Microstrip antennas are used for the

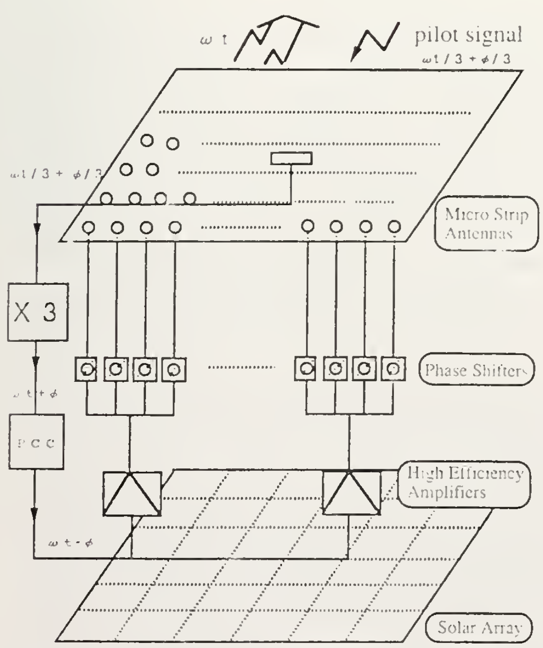
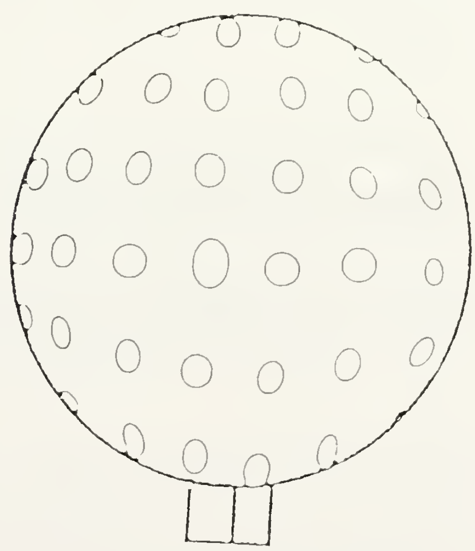


Fig. 3 A block diagram of the autonomous microwave transmitter module for the PSS

active phased array of the autonomous transmitter module. Inter-antenna distance is chosen to be a half wavelength (~0.63cm) to suppress the grating lobes.

The merit of using the microstrip antennas is its light weight and easiness of their mass production.

A sphere-shaped rectenna is recommended to attain the omni-directional directivity as shown in Fig.4. Each antenna element imbedded on the surface of the sphere-shaped balloon is a crossed dipole to achieve a light-weight rectenna.



Rectennas on Sphere Balloon

Fig. 4 Rectennas imbedded on the surface of a Balloon with omni-directional directivity.

4 Missions of the PSS

Possible missions of the PSS are:

1. Power transmission to small satellites
2. Power transmission to space stations

3. Experimental tests of energy transmission via microwave in space.

The first two missions have practical purposes providing a unique infrastructure of a large power ($\sim$100kw) supply to customers through a light-weighted and simple rectenna system. The third mission is a verification test of the functions of the transmitter modules and beam control system developed and adopted for the PSS.

The tests will cover

1. Pointing accuracy and time response of the microwave energy beam,
2. Spatial distribution of the transmitted power produced by the side and grating lobes of the transmitter,
3. Frequency stability of the FET microwave generator and its noise characteristics,
4. Heat control of the module,

   and

5. Attitude stability and mechanical distortion of the large disc of the modules.

Details of each elemment of the PSS will be presented at the Conference.

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B2.3 Small-scale space power station: Feasibility and usage prospects

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ABSTRACT

The problems directly concerning the creation of an orbital solar power station is considered in practice. It is recommended to concentrate efforts on small-scale power stations of 250-500 kW, designed for energy supply of local terrestrial users. Generalized design characteristics of a low-orbit, energy-accumulating solar power satellite are given. It is proposed that an international program of R & D to produce a small-scale, energy-accumulating LEO satellite should be implemented.

Modern electric energy generation methods depend on burning of fossil fuels which causes adverse environmental effects. Further expansion of industrial production increases energy consumption on a world-wide scale. It means that despite the measures to save energy and economize fossil fuels their consumption will grow and the planet's mineral resources will continue to be exhausted. Uncontrolled energy resources consumption growth gives rise to ecological problems - increasing environment pollution and worsening of the environment people live in.

To protect the Earth biosphere against extremely adverse effects of the energy production industry it is necessary to develop alternative methods of energy production. These methods may include nuclear power plant construction, utilization of restorable energy resources (solar, wind, tidal and geothermal energy), and change of the people's way of life with the purpose of reasonable self-restriction of energy resource consumption. Much is expected of extensive utilization of the solar energy coming to Earth. The energy of our Luminary is tremendous and ecologically pure. Its terrestrial conversion and utilization do not result in harmful effluents, environmental contamination or an additional warming-up of the Earth. However, due to the complexity of practical implementation solar energy will remain an auxiliary energy source for a long time and cannot replace the now available energy sources.

K.E. Tsiolkovski, the theoretical astronautics founder, was the first to have payed attention to a well-known fact - irretrievable loss of solar radiant energy for mankind - and to have searched for ways to use this energy. In his work, "Exploration of Universe Spaces Using Jet Apparatus", K.I. Tsiolkovski wrote : "Jet apparatus will win unlimited spaces for mankind and give the quantity of solar energy two billion times greater than that mankind has on Earth". Liquid-propellant rocket should become a real means of accomplishing a space flight, allowing lift-off and deployment of special orbital facilities for solar energy utilization.

After the space age forecast by K.E. Tsiolkovski began the first American (January 1958) and third Soviet (May 1958) satellites were equipped with solar power plants using photovoltaic energy converters.

After the first satellite launches a flyer and a well-known advertiser of aerospace technology, N.A. Varvarov heading the Astronautics section of the U.S.S.R. Voluntary Society for Cooperation with the Army, Air Force and Navy in the middle of the fifties, put forward an idea of supplying terrestrial users with unlimited electric energy with the help of special spacecraft - orbital solar power stations. He ardently advertised this new concept using press, radio as well as conferences and symposia. In 1960, speaking about potential capabilities and significance of the new-type energy system he wrote in the scientific/popular magazine "Technology to the Youth" : "...man's creative thought will direct its efforts towards the creation of space helioelectric stations, supplying terrestrial users with electric energy in unlimited quantities. It will contribute to saving all kinds of energy sources and to meeting energy demands to the fullest extent.

P.E. Glazer, an American scientist developed the concept of supplying terrestrial users with further space electric energy. In his articles published 1968-1973 he concretely defined a solar power station design outline, described key elements of the orbital solar power station on the basis of prototypes that actually existed.

The contribution of Arthur Clark, a futurologist and fiction writer, to developing the concept of supplying terrestrial users with electric energy from space is worth mentioning. In the book "Outlines of the Future" published in New York in the early sixties, A. Clark convincingly showed the prospects of locating SPS's at close distances from the sun, thus considerably reducing solar panel size.

Thus, the development history of idea and concept of supplying terrestrial users with energy from space obviously acts as proof that the space helioenergetics has three "fathers" : Nikolai Varvarov - Arthur Clark - Peter Glazer. But the priority as seen from scientific publications is given to the engineer from Russia.

During the seventies and eighties specialists from the U.S.A., U.S.S.R. and other countries developed projects of large space power satellites with an effective power of 1-10 min. kW. It would be a huge structure of 20-50.000 tonnes mass with a solar collector or concentrator area of 10-100 sq. km. Specific mass of such a structure would be about 10 kg/kW, and the installed power cost would be $4-5,000 per kg.

To construct the proposed large orbital solar power satellite design would require much investment and reinbursement of the cost would begin 20-30 years after the construction started. The traditional way of developing high power solar electric energy systems was successively to produce low and average power plants providing profitability of each development stage and reimbursement of investments.

The method of creating large electric power station models, having developed first demonstration models of 100-500 MW should be thought of as unlikely. In our opinion, an alternative space energetics development approach is a step-by-step build-up of the electric energy power station from 10 kW to 1 MW, 10 MW, 100 MW, etc. Transfer to the next development phase is made only after reimbursement of outlay and acquisition of necessary experience have been provided at the previous phase.

Each phase must be optimized to solve a given problem. It is known that energy sources of low and average power are in demand in many countries of the world. In remote areas, North Pole regions and on ocean islands there are many production plants which may appropriately use solar energy. Hence, a peculiar feature of the proposed approach will be the energy system profitability at every phase of its development. It will be the only source of savings for funding the next development phases.

Considerable difficulties block the way to creation of small-scale electric power plant models and these difficulties are brought about mainly by the directed microwave power transmission/reception system problem and by the necessity of providing terrestrial users with power supply profitability.

The known technological design of a highly efficient microwave power transmission/reception systems provides for development of orbital and on-ground large-aperture antennae. With power transmission distances of the order of 40,000 km, oscillation frequency of 2.45 GH and transmitting antenna diameter by the receiving antenna diameter should not be less than 10 sq. km. The base model for an orbital powerful electric station will utilize an 1 km diameter orbital antenna and a 10 km ground antenna. Efforts to decrease the size of antennae for small-scale stations to acceptable values (for example, to 30 or 300 m respectively), leads to a catastrophic drop of their efficiency to less than 1 per cent.

At present, due to this, the design of a small-scale SPS on LEO using continuous mode of power transmission/reception is to be considered unfeasible.

Nowadays, the available conceptual developments of a small-scale SPS differ in their orbit structure and design features [1-3]. Generalized design characteristics of such satellites are given in the Table. (Preliminary generalized performances of a small-scale SPS are presented in enclosed slides 1-7).

Table

SPS Performance		**Developing Organization**	
	TsNIIMash U.S.S.R.	**Cosmology Institute Japan**	**Ad Astra, Inc. U.S.A.**
Effective power, kW	250	10,000	500
Operational orbit	LEO, circular	LEO, elliptical	GEO
SPS mass, t	70	200	5.3
including :			
- energy plant	5	180	3.0
- transmit antenna	20	10	1.3
- on-board accumulator	15	part of power plant	-
- structure	5	10	-
- hab module	20	-	-
- reserve mass	5	-	1.0
- specific power plant mass, kg/kW	270.0	20.0	10.6
Power plant size :			
- solar panel or solar collector area, sq. m	0.7 x 10.000	7.2 x 10.000	10.000
- transm. antenna aperture, m	30	100	10

Under the Japanese project a low-power turbo-generator system is integrated with an on-board energy accumulator that permits the lowering of the whole system's mass. At the same time, the transfer antenna's mass seems to be underestimated. The power plant and directed energy transfer system of the US project has extremely high specific performance that seems to be problematic to achieve during the nearest development phase. The Soviet project of a small-scale power satellite has reasonable specific performance. Much attention is paid to the SPS deployment and servicing means. The project would comprise a habitat module - similar to the Mir s - that hosts astronauts who are to conduct adjustment and repair work. It is supposed that launch, deployment and

servicing of a small-scale SPS would be done by using available technical means - a superheavy lift Energia booster, a Progress supply spacecraft and a manned Soyuz-type spacecraft.

Out of the whole set of problems needed to be solved at the nearest phase one should stress the following :

- theoretical and experimental basing of feasibility of the proposed technical solutions (mainly coupled with the directed energy transfer system and on-board accumulator);
- achievement of acceptable mass/energy performance of the main SPS elements;
- cutting development, manufacturing, deployment and operational costs of a new type of power system;
- meeting environmental demands and ensuring compatibility of existing ground and space radio systems with an SPS.

Let us touch upon the cost-effectiveness problem. Assuming that the average cost of spacecraft development and orbit delivery cost corresponding to the Soviet commercial tarif ($4000 to $5000 per kg and $2000 to $3000 per kg respectively) one may calculate specific capital investment of output energy generated by the system. The investment is about $1 to $2 million per kW. It is known that the existing ground solar power systems and those under development of 1 to 10 MW level require investments of about $5,000 per kg. It means that to deploy an SPS requires investments of 400 to 500 times more than the cost of terrestrial solar systems.

At the same time, designers see good possiblity to cut the SPS mass and increase efficiency of energy transformation and transfer/reception that leads to investment decrease. Additionally, high power level system employment cuts specific mass and subsequently investment.

A small-scale SPS along with local consumer supply may simultaneously solve other important tasks. It may become an energy base for orbital productive facilities and space stations of new generation. The need of practical implementation of a small-scale SPS should be considered as an urgent task of modern space technology development. In order to solve this problem there are many preconditions : great experience of different space power equipment development, theoretical base needed to design direct microwave beam energy transfer/reception a number of effective space transportation systems available and great operational experience of economy-orientated space systems.

Most effectively existing problems may be managed in the framework of an international program.

A research/development program including experimental work will permit the involvement of great mental resources and advanced technology development.

By the way such an international cooperation is being established now. We have discussed main problems with some US organisations. Plans to work on an international SPS science and technology program with the participation of Japan, USA and Germany are already announced.

Authors of this paper propose working out an international program aimed at the deployment of a small-scale SPS of 250 to 500 kW effective power level by the year 2000 to 2005. Assuming that solar energy utilization is in favour of all mankind, it is advisable to fund the development from international resources (for instance, from UNO's science and technology fund). Such a program would be in the basic interests of people and promote trust and mutual understanding between nations. In the framework of the program we should also investigate problems connected with a large-scale high power level SPS and prospects of global space solar energetics.

In the case of our initiative being supported we propose to organize here at the symposium an International Public Committee to start such a program and establish its working bodies. Within the current year the Committee would issue a directive documents package and address them to concerned international organizations and governments for their consideration and authorization.

Representatives of the Soviet science and industry circles are ready to participate actively in small-scale power satellite development.

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BASIC DESIGN CHARACTERISTICS OF LOW-ORBIT, ENERGY-ACCUMULATING SOLAR POWER SATELLITES

I. GENERAL PERFORMANCE

Effective power	- 250 kW - 500 kW - 1000 kW
Orbit - solar synchronous circular isotrack pattern	($h \approx 500$-600 km $i = 97.5°$)
Satellite power plant generating mode	- Continuous
Power transmission/reception mode	- Quasi-momentum
Power supply mode for terrestrial consumption	- Continuous
Power generation type facility	a) Photovoltaic converters (Silicon solar batteries) b) Turbo-generating converter
Directed power transmission/reception system	- SHF link
SHF radiation wavelength	- 1 - 2 cm

BASIC DESIGN CHARACTERISTICS OF LOW-ORBIT, ENERGY-ACCUMULATING SOLAR POWER SATELLITES

II. SYSTEM EFFICIENCY PARAMETERS

	Solar Batteries	Turbo-generating Unit
Total system effectiveness per cent	2.7	8.3
Including :		
Power generator efficiency	13	40
Satellite power storage efficiency	80	
Efficiency of electric power conversion into SHF radiation	82	
Downlink transmission efficiency	60	
Rectenna reverse conversion efficiency	70	
Terrestrial power storage efficiency	80	
Interface line efficiency	95	

BASIC DESIGN CHARACTERISTICS OF LOW-ORBIT, ENERGY-ACCUMULATING SOLAR POWER SATELLITES

III. ENERGY CHARACTERISTICS

Energy storage time	12 hours
Energy transmission/reception time	2.5 min.
Energy transmission/reception around the clock cycle number	2

	Solar Batteries	Turbo-generating Unit
Solar radiation flux power, utilized by satellite power plant, kW	9260	3015
Power plant generating capability, kW		1220
Satellite storage capacity, kW/hr.		14550
Power fed to antenna, kW		$2.79 \cdot 10^5$
Radiated power, kW		$2.28 \cdot 10^5$
Power fed to rectenna, kW		$1.37 \cdot 10^5$
Terrestrial power storage input, kW		$0.96 \cdot 10^5$
Terrestrial power storage capacity, kW		4000
Terrestrial power storage output, kW		264
Effective power, kW		250

BASIC DESIGN CHARACTERISTICS OF LOW-ORBIT, ENERGY-ACCUMULATING SOLAR POWER SATELLITES

IV. DIMENSIONS

A. Photovoltaic power unit :

- Solar collector area	$0.66 \cdot 10^4$ m^2
- Solar battery size	35m x 100m
- Solar panel number	2

B. Turbo-generating power unit

- Solar concentrator area	$0.22 \cdot 10^4 m^2$
- Solar concentrator diameter	53m

C. Directed energy transmission/ reception system

- Transmitting antenna diameter	30m
- Receiving antenna diameter	300m

BASIC DESIGN CHARACTERISTICS OF LOW-ORBIT, ENERGY-ACCUMULATING SOLAR POWER SATELLITES

V. SPECIFIC MASS CHARACTERISTICS

A.	Photovoltaic power unit	
	- Solar collector specific mass	0.5 kg/m^2
B.	Turbo-generating power unit	
	- Solar concentrator specific mass	2 kg/m^2
	- "Heater-turbine-generator" system specific mass	15 kg/kW
	- Cooler-radiator specific mass	3 kg/m^2
C.	Flywheel-type power accumulator	
	- Specific mass	1000 Whr/kg
D.	Transmitting antenna	
	- SHF instruments and waveguides	0.02 kg/kW
	- Load-bearing structure specific mass	10.0 kg/m^2

BASIC DESIGN CHARACTERISTICS OF LOW-ORBIT, ENERGY-ACCUMULATING

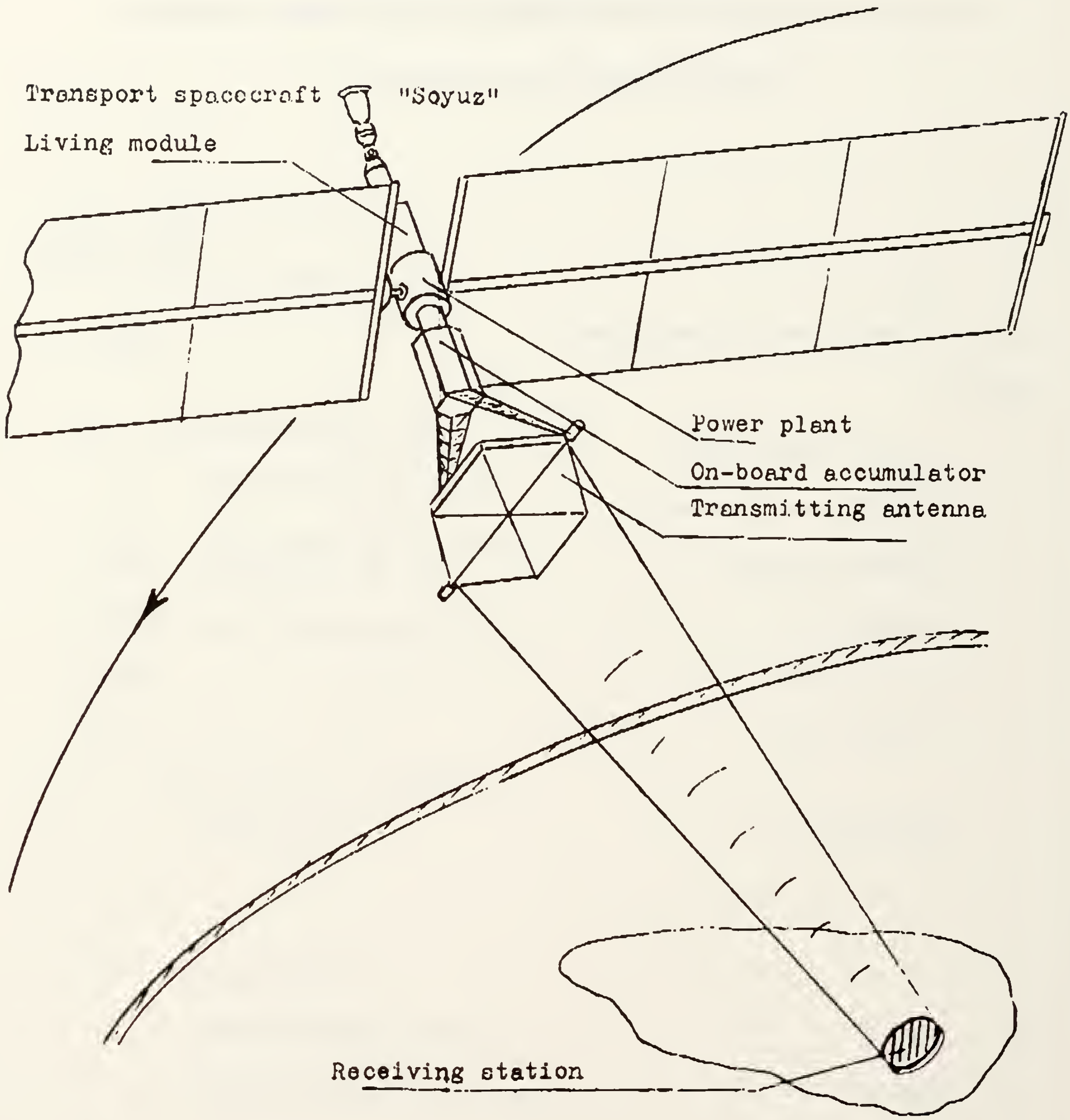
SOLAR POWER SATELLITES

VI. SMALL-SCALE SOLAR POWER SATELLITE MASS CHARACTERISTICS

		Relative Weight
Molel power satellite mass in its operating orbit,	70	100 %
Including :		
- Power unit (photovoltaic)	5	7.1
- Satellite power accumulator	15	21.4
- Transmitting antenna	20	28.6
- Construction	5	7.1
- Living module	20	28.6
- Reserve mass	5	7.1

GENERAL VIEW OF LOW-ORBIT, ENERGY-ACCUMULATING

SOLAR POWER SATELLITE



B2.4 The IGRE's 100 kilowatt demonstration project

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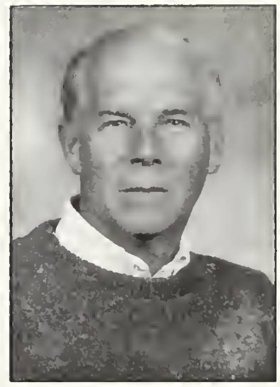

ABSTRACT

It is asserted that a low cost demonstration project is the only way that both the market resistance and inertia of government agencies will be overcome. Using Soviet launchers and terrestrial type solar cells a 100 kilowatt demonstration project is possible for approximately 150 million dollars. Using a Soviet Topaz II nuclear thermonic reactor, higher frequencies, a nuclear safe orbit of 900 km and a PROTON launcher a 20 kilowatt demonstration project for less than 100 million is possible.

RESUME

Un projet de démonstration de coût réduit représente la seule réponse à la résistance du Marché et à l'inertie des agences gouvernementales. En utilisant des lanceurs soviétiques et des cellules solaires de type terrestre, un projet de démonstration de 100 kilowatts devient possible pour la somme approximative de 150 millions de dollars. Avec l'emploi d'un réacteur thermonique nucléaire soviétique Topaz II, des fréquences plus élevées, d'une orbite dénuée de risques nucléaires de 900 kilomètres et d'un lanceur PROTON, un projet de démonstration de 20 kilowatts est réalisable pour moins de 100 millions de dollars.

Introduction

I am concerned about the future because that is where I will spend the rest of my life.
- Charles Kettering

IGRE are the initials for the Institute for Global Rural Electrification, a planned not for profit entity whose purpose would be to promote the concept of using energy from space to help developing countries achieve sustainable, environmentally benign development. One goal is to either raise funds for carrying out a demonstration project or to disseminating the idea of doing a small demonstration project.

A reason for considering creating such a foundation is the author's perception of the inability of the government to execute a small, hardware oriented, as opposed to paper studies, project in a timely and cost effective manner. Within the government process, with or without results, has become more important than producing a quality product in a timely and cost effective manner.

This paper presents a rationale for undertaking the development of power from space and why a small demonstration project is a logical first step. The paper goes on to describes the IGRE 100 kW demonstration project and the costs associated with it. The significance of the undertaking is pointed out and an explanation of why the project has not been undertaken before is offered.

Rationale for Power from Space

"No nation including the United States can remain strong and disciplined as a people without some sense of purpose ... What then is the new sense of purpose... which can rally our people?" W. E. Hadley, Executive Vice President, Bank of America, in comments to the Commonwealth Club of California, Jan 4, 1980.

The Report of the Advisory Committee On the Future of the U.S. Space Program stated in its executive summary that there is a lack of national consensus as to what should be the goals of the civil space program. Then in the body of this report they make, as they put it, "an important observation."

"A lesson that history offers is that the space program seems to work best, ..., when there is an overreaching goal that can generate public support and focus the technological infrastructure on tangible goals."

We can assume that the history lessons refered to The Manhattan Project and Apollo. Both projects had a moral imperative, win the war or beat the Russians.

An unfortunate aspect of those history lessons is that it has given both the general public and technologists a mistaken paradigm for technology development and implementation - giantism, heroic efforts and a presidential decree. I admit to the very same failings. For years I thought that all we needed was for the President to say go. Lately I have come to realize that a Presidential decree is a little like the Emperor's new clothes. There may be nothing there but you won't find anyone in the administration willing to tell him he is all wet and that Mars won't sell well on main street.

However, the Manhattan Project and Apollo were technically successful because the supporting technological infrastructure, educated and trained people as well as manufacturing skills, were ready and available in sufficient quantities to support a major initiative. Such is not the case with President Bush's statement that we should go to Mars in 20 or 30 years.

Also forgotten is that the space program moved rapidly through a series of demonstration experiments under the names of Mercury, Gemini and a series of Apollo launches. Boosters were evolved and then created in parallel to the successful launches. Proponents of the U.S. Space Station Freedom and concepts for satellite power systems have forgotten or never learned the history of technology.

I propose that the commission to develop power from space as an environmentally benign source of energy, especially if it comes from a broad spectrum of industries and the people, provides the needed moral imperative and overreaching goal and focus needed by most space programs in the world. However, how to begin? Where is our series of rapid paced experiments?

Rationale for a Small Demonstration SPS

The Report of the Advisory Committee On the Future of the U.S. Space Program listed five attributes that an ideal space program would have. Three of those attributes are applicable, in my opinion, as a justification for structuring a series of small demonstration projects ranging from a small power satellite to the robotic exploration of the geology of the Moon. The attributes and how they are related to a small scale demonstration are listed below.

A Challenging set of space missions, strongly supported by the American people over extended periods because it contributes to the nation's well being and is affordable.

Energy and the Environment are pressing issues. Power from space provides a way to link the challenge and mystery of space exploration with the needs and concerns of the people of this biosphere. Meeting those needs will generate the support needed to sustain the effort over extended periods of time.

Starting with a small scale demonstration project a set of space missions can be designed to develop the resources of Greater Earth, which are affordable and have short time periods for completion. Greater Earth is a phase coined by Congressman George Brown (D-CA), Chairman of the House Committee on Space, Science and Technology, and means the resources of the dual planet system, Earth and the Moon as well as the energy of the sun.

Starting with a small scale demonstration of power from space the effort to develop an environmentally benign source of energy based on the resources of Greater Earth will entail a challenging set of missions ranging from small prototype demonstrations on up to a level of effort similar to that of a Panama Canal, the TVA, the Manhattan Project or the Alaskan Pipeline. Some of the missions that will be enabled by the quest for power from space are:

- Demonstrating power from space
- Robotic geological prospecting of the Moon
- Development of Space Nuclear Power and Propulsion systems
- Constructing large power systems in space
- Construction of a lunar base and support facilities in LEO in lieu of a space station.
- Exploring the moons of Mars for volatiles, the asteroids for minerals, and the skies of Jupiter for hydrogen and helium-3.

By being humble and willing to start small we can, as our forefathers before did with railroads, automobiles and airplanes, evolve the needed infrastructure on a pay as you go basis. There is no need to leap from concept to giant power systems in the sky. We and society need to grow into the concept that the resources of Greater Earth:

- Changes the Club of Rome's Limits to Growth equations and
- Provides a means for achieving a just and sustainable development ethic for the globe.

An effort that yields visible and significant results., so that the American taxpayer can justifiably believe that the organization is accomplishing its mission efficiently, effectively, and in a fiscaily responsible manner while contributing to our pursuit of knowledge, the quality of life here on Earth, and to the inspiration of all peoples.

Power from space as an environmentally benign source of energy for sustainable development in the Third World will provide an inspiration and hope to all people while improving their quality of life. The quest for energy will take us to the Moon and beyond and such travels will force us to learn more about ourselves, our planet and our solar system.

Small demonstration projects and technology test bed systems are possible today. They would be visible and they are needed for both testing and for demonstrating the immediate benefit of the space program. Without a lot of study a 10 to 100 kilowatt system could be deployed within 4 years. Once deployed results would be apparent almost immediately rather than having to wait 10 years for the probe to get to a planet or for data to be reduced to x number of Phd theses.

A series of projects, starting with a small demonstration power satellite, allows for management accountability and Congressional oversight. Multi-year funding of a four year, low ticket project is probably easier to shallow than granting a 10 year blank check for a gold plated monument.

A set of space program building blocks and technology achievements that can be clearly related to the overall mission and affordability levels.

The successful demonstration of beaming power to a rural village in the Third World will justify undertaking the technology development of a number of items such as

- An equatorial space center located in Kenya.
- A mass driver for construction materials located on the western slope of the Andes in Peru.
- A lunar base and mass driver for supplying lunar materials for building more power satellites.
- Heavy lift launch vehicles.

This development effort would also cover such areas as lunar soil mechanics, utilization of in-situ resources, design methodologies and adapting construction techniques developed for such hostile environments as the arctic. A broad effort which reaches out to encompass other industries than just aerospace.

Some of these programs are the same building blocks that a manned Mars mission would eventually require. The difference being that the development of the technology for power from space has a moral justification, provides visible and significant results and perhaps in the long run be justified economically..With a robust infrastructure in place and providing income and benefits to Earth it becomes economically feasible to consider a scientific mission to Mars.

Project Description and Costs

This section of the paper contains a brief overview of the system followed by a brief history of the concept, subsystem details, and a cost analyses of the IGRE 100 kilowatt demonstration project.

Description

System Description: The basic system consists of an array of photovoltaic cells located in geosynchronous orbit, a orbit in which a satellite appears to be stationary over one spot. The power produced by the solar cells is fed to microwave generators which are coupled to a transmitting antenna. The microwave beam is focused on a receiving antenna on the ground which converts the microwave energy into electrical energy. There are no effluents and contrary to both fossil and nuclear power plants there is no waste heat to be rejected using cooling towers or rivers and lakes.

History: Peter Glaser first described the concept of beaming power to Earth in an article in Science, Glaser, 1968. He has expanded on the concept in numerous articles since then. One such article, Glaser, 1975, discusses in some detail the solar power satellite as an energy option for Earth.

DOE and NASA participated in a joint systems study which created an extensive

library of studies and papers along with a proposal for a 100 billion dollar research and development program. Such programs are now called technology development.

NASA assumed the best case situations and derived a cost of power of about 4.5 cents per kilowatt-hour. The National Research Council (NRC) issued a report in 1980 which essentially killed the concept. In their report they assumed worst case situations particularly with launch costs and derived a cost of power of approximately 20 cents per kilowatt-hour.

Based on the NRC report, the shuttle development program and a wanning energy crises the U.S. abandoned yet another promising technology. Meanwhile the Strategic Defense Initiative has advanced many of the needed technologies particular those related to higher frequency microwave generators, beam focusing and aiming. Many nations have pursued the concept of Solar Power Satellites. In 1986 the French hosted the first international conference on power from space.

Details: Previous concepts have focused on using a frequency of 2.45 gigahertz (GHz) because: a) there is a water window, i.e. the microwave energy pass through water molecules in the atmosphere rather than be absorbed and b) the frequency is in a bandwidth set aside for industrial applications rather than communications. Power levels are limited to 23 miliwatts per square centimeter where the beam passes through the ionosphere in order to avoid any interaction with the atmosphere. At the edge of the receiver power levels are limited to an intensity which is midway between the U.S. and U.S.S.R safety standards fro prolonged exposure to microwave energy.

Although there are many antenna designs possible, Balanis, 1984, the need to extract useful power from the beam appears to require a wavefront which arrives at the receiving antenna in phase across the diameter of the receiver. This requirement is described by diffraction limited optical theory, Feynman, 1963, and results in rather large transmitting and receiving antennas at the 2.45 GHz frequency. Higher frequencies result in smaller antennae. Table 1 compares antenna size as a function of frequency. The derivation can be found in Feynman, 1963 or Leonard, 1991.

Table 1 Antenna Size as a function of frequency.

Frequency (GHz)	Wave length (cm)	Transmitter (meters)	Receiver (kilometer)	Approximate Max. Power Received(MW)
2.5	11.99	1,000.	4.30	3,340.0
		100.	43.04	
10.0	3.00	1,000.	1.08	210.7
		100.	10.77	
50.0	0.60	1,000.	0.22	
		100.	2.15	835.0
100.0	0.30	1,000.	0.11	2.2
		100.	1.08	210.7

Solar Array: We assume a solar intensity of 1.35 kilowatts per square meter of solar radiation in geosynchronous orbit and a solar array conversion efficiency between 11 and 15 percent. These assumptions result in, at 15 % efficiency, an electrical output of 202.5 watts per square meter and 4.94 square meters per kilowatt. A 100 kilowatt power array will be approximately 20 meters by 25 meters in size.

If space qualified lightweight solar cells are used the bare bones weight for a 100 kW system would be 909 kilograms based on data furnished by Lockheed. If terrestrial solar cells were used, a two orders of magnitude reduction in cost, the bare bones weight of the power system would be 9,120 kilograms.

Microwave Generator: During a telephone call in 1988 Varian provided me the following data with the understanding that it was for a conceptual study and small quantity purchase. The performance and cost data is based on a Varian stock single frequency tube, SK70SHI, in the 2.45 Gigahertz range. The tube produces 30 kw of microwave energy from a 22.5 kva/2.7 amp power supply. It requires liquid cooling. In order to use forced air cooling you have to drop to power levels on the order of 1 to 2 kilowatts.

The weight of the SK70SHI unit is 286 pounds. This works out to 9.5 kilograms per kilowatt. For a 100 kW system the mass 950 kilograms.

Transmitting antenna: This is a key item for a low power system. Previous studies locked on 2.45 GHz as a desirable frequency with the result you needed a very large antenna in space. Using DOE/NASA reference systems data to determine the unit weight of the antenna we get 2.7 kilograms per kilowatt of power transmitted. It is not clear for the weight statement if this weight includes the weight of the microwave generators. In any case the weight for a 100 kW system comes to 270 kilograms.

Table 2 is a summary of mass based on the above discussion. It is thought by the author that the weight of the terrestrial type solar cells is a bit high. However the point to note is that from a weight standpoint only, i.e. ignoring volume limitations, that the 10,340 kilograms is well below the 19,500 kilogram payload capability of either the Soviet PROTON or the U.S. Titan IV launchers.

Table 2 - Summary of Mass for a 100 kW Power Satellite.(kilograms)

Subsystem	Weight	Weight
Solar Array		9,120.
Solar Cells	9,120.	
Structure		
Power Dist.		
Control Sys.		
Microwave Gen.		950.
Antenna		270.
Transmitter		
Structure		
Power Dist.		
Control Sys.		
Interfaces		
Ion Thrusters		
Propellant (LEO to GEO)		
Station Keeping (thrusters & propellant)		
Sat. Control Sys.		
Total		10,340.

Chain efficiency from the bus bar of the solar array to transmission is 62 %. This means of the hundred kilowatts of electrical energy available at the busbar in space only 62 kilowatts is beamed down to Earth.

<u>Ground System</u>: The ground system consists of a receiving antenna which for diffraction limited optics and the need to collect the energy in phase of the entire surface of the antenna is flat and perpendicular to the wavefront. An alternative might be to use an undulating antenna if the power beam was steady enough. Details of the rectenna as the receiving antenna is called can be found in a variety of references with Glaser, 1975 being a good starting point for finding the correct citations.

Assuming a diffraction limited antenna design and a 100 meter transmitting antenna the ground antenna would have a diameter of 2 kilometers for a 50 Gigahertz system and 1 kilometer for a 100 Gigahertz system.

Looking only at the power density limit of 23 mw/cm^2 in the atmosphere the ground antenna would have a minimum diameter of 18.5 meters for a 62 kilowatt power beam. This should be assumed to be a design challenge.

<u>Cost Estimate</u>

"Miscalculation or sheer ignorance of cost and difficulties was the key to launching a number of great and successful enterprises, from canals and railroads to mining and manufacture."

- Sawyer, 1952

Not that I propose that we proceed on a project of such magnitude and impact in ignorance but rather that at some point in time you have to move forward in the confidence that you will succeed even if you do not have prefect knowledge of the risks and costs.

<u>Assumptions</u>: The major assumptions behind the IGRE 100 kilowatt demonstration project are: 1) use of terrestrial solar cells at between 3 and 5 dollars per watt as opposed to NASA solar cells at a thousand dollars a watt and 2) use of a Soviet Proton launcher for 30 million dollars per launch (1,540 dollars per kilogram), Jane's Spaceflight Directory, 1987-1988, page 465. An additional assumption is that transfer to geostationary orbit is accomplished using proven, i.e. tested ion thrusters powered by part of the solar array.

<u>Microwave Generator</u>: The cost data is based on a Varian stock single frequency tube, SK70SHI, in the 2.45 Gigahertz range for a small quantity purchase. The cost for a tube and magnet is approximately 95 thousand in 1988 dollars for a 30 kW unit. Unit cost is approximately 3,200 dollars per kilowatt. Taking in the drops in energy due to system efficiencies we need approximately 90 kilowatts of tube capacity for a total cost of

<u>Ground System</u>: Antenna and atmospheric losses result in the receiving antenna seeing between 81 and 86 kilowatts of energy. The NASA/DOE reference system used a cost of 1,377 dollars (1986) per kilowatt. Leonard, 1988, in an independent cost derivation based on construction industry standards arrived at a cost of 5,200 dollars (1988) per kilowatt. The difference in cost per kilowatt-hour is 4.72 cents with the DOE/NASA cost being 1.7 cents per kilowatt-hour. The two costs shown are for a 20 meter diameter receiver and a 1 kilometer diameter receiver. Both are costed using the 5,200 dollar estimate.

It is obvious from the data shown in Table 3 that unless the antenna sizing problem can be solved that small demonstration projects using geosynchronous orbit are not economically feasible. There is however a tremendous economic incentive to work the antenna design problem.

A question to be raised, especially for a demonstration project, is do you have to collect all of the energy beamed down? For instance I could collect the power from a 100 meter diameter receiver and conduct long duration exposure experiments in the remaining area of the 1 kilometer effective aperture area. A 100 meter diameter receiver has an installed cost of approximately 41 million dollars.

Table 3 - Summary of COSTS for a 100 kW Power Satellite.(millions $)

Subsystem	Low	High
Solar Array		
Solar Cells	0.500	100.000
Structure		
Power Dist.		
Control Sys.		
Microwave Gen.	0.288	0.288
Antenna		
Transmitter		
Structure		
Power Dist.		
Control Sys.		
Interfaces		
Station Keeping		
Sat. Control Sys.		
LEO/GEO Transfer		
Earth to LEO	30.000	250.000
Rectenna 20 m dia	1.634	
1 kilometer dia.		4,084.070
100 meter dia.	40.841	
Power Conditioning		
Connect to Grid		
Design-Integration	20.000	
Project Management	10.000	
Total	103.263	

Summary: The cost, if advantage can be taken of the Soviet launch capabilities, is probably below 200 million. Although limitations imposed by antenna design may not let you, from a cost stand point, collect the full amount of energy a useful demonstration of technology could be carried for a reasonable amount of money within a short time period. Using U.S. launch capabilities and the same assumption of a reduced size antenna the costs are in the 400 to 500 million dollar range. Successful demonstration of the technology will prove that a national, not NASA, space program can provide tangible benefits. In addition it will provide us with a test bed for investigating the health and environment issues before large systems are started.

Summary: The test program would consist of a 100 kW array of terrestrial type, space qualified solar cells, (20 meters by 25 meters), microwave generators operating at about 90 to 100 GHz, if the atmosphere is transparent to this frequency and a 100 meter diameter receiver. I would hope that the site would be located in one of the following countries, China, India or Kenya. The satellite would be place in LEO by a Soviet Proton and transferred to GEO using an ion thruster.

The cost for a 100 kW demonstration of power beaming from GEO to Earth is probably below 200 million if advantage can be taken of Soviet launch capabilities, i.e. PROTON with a 19,500 kg payload to LEO. Limitations imposed by antenna design may not let you, from a cost standpoint, collect the full amount of energy. Regardless of antenna limitations a useful demonstration of technology could be carried for a reasonable amount of money within a short time period. Using U.S. launch capabilities and the same assumption of a reduced size antenna the costs are in the 400 to 500 million dollar range.

Successful demonstration of the technology will prove that a national, not NASA, space program can provide tangible benefits. In addition it will provide us with a test bed for investigating the health and environment issues before large systems are started. Details are listed in the following paragraphs.

Other Possibilities and Proposals

An alternative to the use of a solar array would be to use a Soviet TOPAZ II reactor to power 10 to 20 kilowatts of microwave generators. In addition, a number of other papers on this topic, Nagatomo, 1991, Richarz, 1991, and Mozjorine et al, 1991, will be presented at this symposium.

Status of Technology

The National Research Council at the direction of the National Academy of Sciences and in response to a request by the National Science Foundation performed an independent review of the DOE/NASA solar power satellite concept. A general conclusion of the NRC report, 1981, was that, "*Some type of SPS would be technically possible if costs were not a consideration*," (p. xx). Details of

where the technology has moved since then are given below for solar cells and microwave generators.

Solar Cells:

Current U.S. space qualified solar cells are 8 by 8 centimeters and have an 8 mil thickness. They are mounted on a kapton backing. The current arrays have a power to weight ratio of 66 to 110 watts per kilogram. The cost quoted in a phone call by a Lockheed engineer is around a thousand dollars a watt with government documentation. He thought you might be able to get the same cells without government documentation for about 350 dollars per watt. All costs in 1988 dollars. These cells have between 12 and 15 percent efficiency. In summary space qualified cells have the following characteristics: 4.94 square meters per kilowatt, 15 to 9 kilograms per kilowatt and a cost of one million dollars per kilowatt.

Solar arrays for terrestrial applications can be purchased for approximately 3,250 dollars per kilowatt. These cells have an approximate efficiency of 12 percent. They are mounted in an aluminum frame with a glass cover and a structural backing. The arrays, with frames, weigh about 13.5 kilograms per meter. Stripping off the frames, cover glass and structural backing the current arrays have a power to weight ratio of approximately 24 watts per kilogram, assuming a 1.34 kilowatts per square meter solar constant and a 12 % efficiency. All costs in 1988 dollars. In summary terrestrial solar cells have the following characteristics: 6.2 square meters per kilowatt, 42 kilograms per kilowatt and a cost of 3,250 dollars per kilowatt.

Gallium arsenide cells have been manufactured which have an 18% efficiency. These are experimental and offer the promise of significant cost reduction due to increased efficiency and the factor they can be operated at higher temperatures, which allows for concentration. The questions are: can they be manufactured at a competitive cost and are there enough natural resources available to support the massive use of gallium arsenide cells. From the viewpoint of completing in the near term a small, low cost demonstration program of power beaming as opposed to cell production gallium arsenide is probably not a viable option.

For a low cost, near term demonstration we need to look at either space qualified cells at a million dollars a kilowatt or terrestrial cells which might be space qualified at three thousand dollars a kilowatt. If you assume you are paying for all of the launch costs, of say a PROTON, then for a power beaming experiment it makes more sense to go with more heavier cells at a lower total cost. An equation can be setup to look at the tradeoffs between weight and costs.

Microwave Generators: Stuart and Gleave, 1990, report that Martin Marietta is developing for SDIO a 60 GHz transmitter. Other work is being carried out, as evidence by several of the papers, Cha, 1991 and Rybakov, 1991, being presented at the Paris Symposium on higher frequency systems. However, for a low cost, near term demonstration we will want to look at off the shelf technology. Whether this would be 2.45 GHz generators or the more advanced, higher frequency ones will depend upon the availability of both the generators and the receiver technology. In either case the technology is available and reasonably priced such that a private, not-for-profit institution might be able to raise the funds necessary for a demonstration of power beaming.

Significance of the Project

A small project, low cost and well within the bounds of known technology will restore confidence in the U.S. space program. A project which provides environmentally benign energy to a third world country will inspire both current practictioners and students. A project which is fast tracked and has a short schedule will provide proof of concept and justification for adding a second and third phase.

Hurdles, Past and Present

Why hasn't a small demonstration project been undertaken before now? For even a demonstration project to be initiated there are a number of non-technological hurdles which must be overcome. Leonard, 1991b, discusses hurdles related to market development. Other hurdles face research and development proposals.

Primary Hurdles

Not Invented Here (NIH): The Solar Power Satellite concept did not originate within either DOE or NASA. While the concept has its champions the NIH syndrome and lack of champions in positions of either budget allocation or policy making within the two agencies, has defeated, up to now efforts, to fund test and evaluation experiments.

Competition with special interests: SPS has to compete for R&D dollars against space science and flight vehicles in NASA and against

nuclear power and fusion within DOE. These special interests are well entrenched and if there is no new money will generally, without outside intervention, prevail against a new idea especially one which has both technical and cost risk associated with it.

Just say No: In a bureaucracy it is easy to advance in the power structure by saying no as there is minimal career risk associated with this option. This same risk aversion carries over to reviews by peers, i.e. the old boys school. One's technical reputation is not at risk if you state it's not practical at this time. Few ideas including railroads, horseless carriages and airplanes were thought by the experts of their time to be practical or more than technical curiosities. On page xix of the executive summary of the National Research Council report they state: ""The technical requirements and scale of the system, however, are far beyond our experience," (p. xix). However, that did not stop them from just saying no. An editorial comment is that at the time they were attempted so were transcontinental railroads, the Panama Canal, the DC-3, Apollo and the Alaska pipeline.

Sticker shock: Opponents of the SPS concept have used the estimated 100 billion dollar R&D budget and the giant size of the proposed units, 5 to 10 gigawatt, to continually defeat attempts to resurrect study and research on the concept. This is an excellent tactic for defeating a concept you don't like without having to engage in nasty debates.

The Commons Syndrome:

In the subSahara sociologists have identified a form of behavior which in an attempt to maximize one's own profit results in the destruction of the resource. In this case it is the attempt to increase the size of a tribe's herd of cattle relative to all the other tribes. The result has been the desertification of the Shacl and the destruction of all herds of cattle. The concept is relevant to the scramble for research dollars regardless of the damage such a fight might do to the long term health of the program.

In the case of high tech research we have a variation on the commons syndrome which I call the research shark feeding frenzy. This is where a prospect of any new money leads researchers to propose any and all advanced concepts as the perfect solution. However to fund the research you can't fund proof-of-principle experiments. Given enough sharks and the demonstration project is starved for funds.

Two current examples of the commons syndrome or feeding frenzy theory are the recovery of nuclear propulsion technology and power beaming. In the first case the arguement is we've already done that and I can do better with my advanced concept if you just give me the money you would spend on proving old technology.

The other case is similar to the above example with there being two alternatives, laser power beaming and gallium arsenide solar cells. Both hold out the promise of being better but will we have to wait to long before we demonstrate success. As a Russian admiral said "Best is the enemy of good enough"

Process versus Product

Another hurdle is the definitive system or trade study in order to insure you select the optimum configuration. Given enough trade studies by well educated engineers who have never produced a product for a profit and you have a program which has overrun its budget and is behind schedule. However, given both a risk adverse bureaucracy and congress this is the preferred path for most new government funded programs. Two examples of this phenomenon are the space station Freedom and the SPS-100 program. In both cases the U.S. can compare their art work against the hardware of other nations.

In the first case we have 4 billion dollars worth of studies designed to produce, by a specified process, the ultimate space station. Yet it is a design which, according to a number of review teams, is critically flawed from a maintenance and operational standpoint. The process is correct but the product flawed. Meanwhile, the Soviets are flying their third generation space station and adding to it in an incremental and evolutionary fashion. It may not include the latest in modern interior design or the lightest materials but it is in existence.

In the second case, we have 400 million dollars worth of studies which has produced a design for the most advanced and powerful space nuclear power system. However in the process of pursuing the best design we have neglected the need to produce a product. Consequently, we go out and buy a second generation Soviet space nuclear reactor, the TOPAZ II.

The U.S. in its quest to prevent fraud and produce the perfect design which can withstand any and all second guessing by Congress, the public, the General Accounting Office and a variety of government funded

think tanks, special interest groups and lobbyists has created a process which has lost sight of the need to produce a quality product on time, within budget. It is this, process vs product, which has led the author to propose a private, not-for-profit, consortium to fund, build and test a prototype system.

The Idolatry of Giantism

The creation of giant systems stems from one of two factors. The first is a manifestation of a technologist enthusiasm for his work and a reversion to childhood fantasies of what might be. We need these visions for guidance toward the future and for substance for debate about where we want our societies and cultures to go. The problem with these visions of the future is that they often carry a big price tag, which the press seize upon, and they lack a plan for arriving at the destination. The visions such as space colonies, and manned Mars missions, excite the population while the price tag turns off politicians and provides ammunition for opponents.

The Need for Third World Participation

We must have the developing nations participate in the development of power from space. There are a number of reasons for wanting and needing the involvement of the third world which range from the environmental and economically to selfish.

An environmental reason is discussed by the author in SPS-91.60, The environmental benefits of Solar Power Satellites. An economic reason, Market Niches is discussed by the author in SPS-91.59. Both of these papers present a case for the deployment of solar power satellites to take place first in the third world.

There is, however, a more pressing and self-serving reason for wanting to involve the third world. Once we are reasonably sure from a theoretical viewpoint that there is little or no environmental or health risks from microwave power beaming we will need to perform an all up, long duration systems test. Given a risk adverse bureaucracy and the adversarial nature of resolving policy issues in the U.S. it will be impossible to perform such a test in the U.S.. Furthermore, similar conditions plus the lack of open area prevail in Europe. Consequently we are forced to turn to the Developing Countries for a place to establish a test bed.

Site selection will depend upon a developing or emerging nation performing their own risk versus benefit analysis and deciding whether they want to participate. Because of the unknowns, i.e. lack of experimental data, there must be a request to participate by the nation rather than an invitation from the developers. If no nation comes forward this lack of interest may well be a bigger hurdle than the size of the antenna system.

Finally there is the potential for creating a new manufacturing industry for a properly qualified nation. The construction of the receiving antennas offers the potential for one or more countries to develop the manufacturing capability necessary to supply an export market in addition to their own needs. The receiving antenna is an item which can be mass produced and until volume reaches a level to warrant automation will lead itself to being produced in a country with a low labor rate.

Summary and Conclusions

A Mission to Earth to provide energy from space, will extend over decades. It will provide the U.S. and other participating nations with new products, energy from space, and skills. Skills such as the ability to construct with automated equipment facilities in hostile environments. Skills and products with which to compete in the global markets of the 21st century. A quest such as this will provide the new horizons and challenges that man seems to need almost as much as he needs food and shelter

There is now no choice before us. Either we must succeed in providing a rational coordination of impulses and the guts, or for centuries civilization will sink into a mere welter of minor excitements. We must produce a great age or see the collapse of the upward striving of the race.

- Alfered Whitehead

A small demonstration power satellite beaming power to a regional health care center somewhere in theT hird World would be a being of a new great age. An age which would see mankind become stewards of their planet and explorers of their solar system.

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Related Work

This paper is one of four presented at the SPS 91 Conference. Two were cited in this paper. The other is described below. Together they describe a vision for the future based on Solar Power Satellites and a reasonable path which may be taken to transform that vision into reality

SPS-91.58, Economic Impact of Using Lunar Resources to Build SPS Systems, assumes that the demonstration project, SPS-91-61, has been successful and that systems have been scaled up to meet the needs described in SPS-91.59. It also builds on the environmental concerns described in SPS-91.60 and leads one in a logical fashion to the cost effectiveness of using lunar materials.

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B3.1 Novel high efficiency multispectral photovoltaic structures for solar energy conversion in space

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Abstract :
III-V compound semiconductors offer many advantages for the powering of future space stations. The different means of increasing photovoltaic efficiency, power-to-mass and power-to-area ratii are presented, namely multispectral and concentration, with proven results at the research and development scale. Applicability of those high efficiency concepts to solar Powersats is discussed. Finally, the high efficiency monochromatic conversion of a laser beam by specially tailored III-V semiconductors is demonstrated, with the objective of energy transmission in space.

Résumé :
Les composés semiconducteurs III-V présentent de nombreux avantages pour l'alimentation des centrales orbitales de puissance. Les différent moyens d'augmenter le rendement, les rapports puissance/masse et puissance/surface sont présentés, en s'appuyant sur des résultats récents. L'applicabilité de ces concepts aux centrales solaires orbitales de puissance est discutée. Enfin, grâce aux semiconducteurs III-V, les trés hauts rendements de conversion monochromatique pour la transmission spatiale d'énergie par laser sont illustrés par une étude récente.

I. Introduction

The production of electricity in space through power systems such as SOLAR POWER SATELLITES (SPS) requires efficient energy conversion. Photovoltaics (PV) is a way of producing electricity directly from the solar beams, provided appropriate semiconducting materials are used.

To achieve the maximum PV conversion efficiency, a primary condition is a good matching of the electronic structure of the chosen material to the solar spectrum. There should be a trade-off between the two types of inevitable intrinsic losses, associated with any photoelectric effect produced by polychromatic photons, as for example in the case of the incident solar spectrum, shown on figure 1. Denoting by E_g the threshold energy of the PV effect, i.e. the bandgap of the solar cell semiconductor, they occur for $h\nu \neq E_g$, $h\nu$ being the

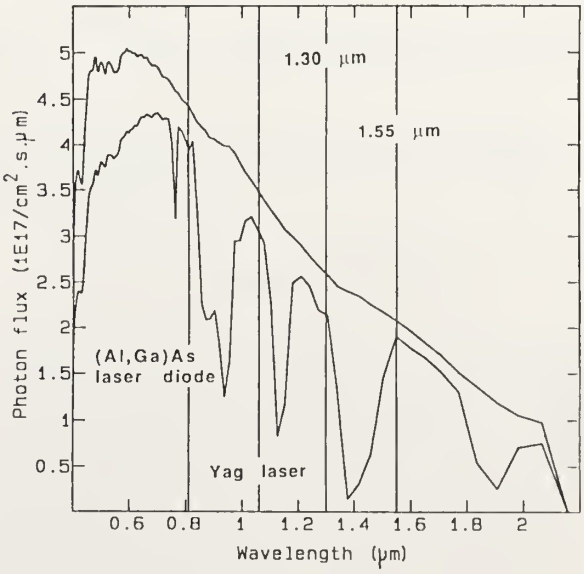

Figure 1. Solar photon spectral flux for different air masses

photon energy. If $h\nu < E_g$, one has transparency losses : photons which go through the cell without being converted. If $h\nu > E_g$, one has excess energy losses. In this case, only a part of the photon energy is converted since, with quantum efficiency equalling one, each incident photon gives one electron and the excess energy $h\nu - E_g$ is lost in the thermalization de-sexcitation process. It is found that E_g should be in the range 1.2 to 1.5 eV (Fig.2), in order to approach the maximum theoretical efficiency of **single** material conversion : a limiting practical value in the range 25-28 %.

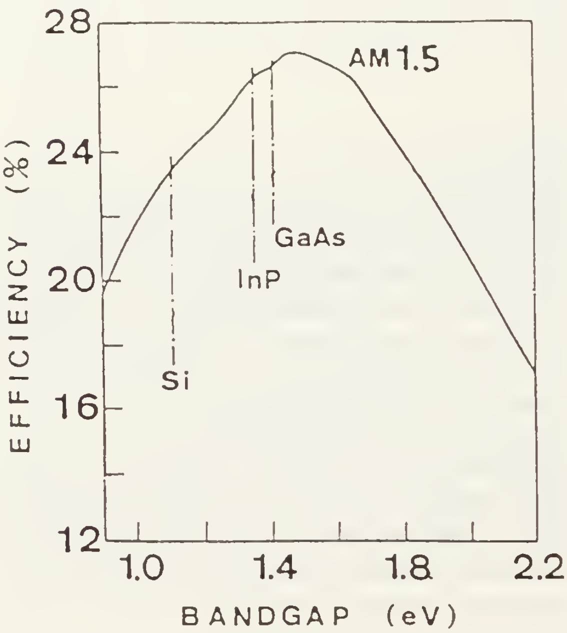

Figure 2 : Practical limit of PV cell efficiency as a function of the bandgap (C = 1).

A second but not least condition is the use of a high purity crystalline covalent or quasi-covalent material [1] and, to achieve efficient and stable devices, the preparation and technology of this material must be fully mastered.

Three materials respond to these conditions : silicon, gallium arsenide and indium phosphide (Si, GaAs and InP). Si, the exemplary covalent semiconductor, has a broad technology base. It is well known in the microelectronic industry and the large majority of presently flying satellites is equipped with Si solar cells. They are produced industrially, both for space and terrestrial applications. However, the bandgap of Si, 1.12 eV, would not allow them to achieve an efficiency greater than 24 % in space.

Alternative semiconductors, for high efficiency solar photovoltaics, have to be selected in the quasi-covalent semiconducting materials, like the III-V compounds [1] . Examples are GaAs and InP.

InP is adapted to the solar spectrum (E_g = 1.35 eV). However, its cost is prohibitive and its fragility makes its use for large area devices like solar cells extremely critical. GaAs (E_g = 1.43 eV) is a good candidate to answer to the three above mentionned conditions . Its electronic structure and crystalline properties should permit to approach the theoretical limit of solar conversion efficiency. Furthermore, its optical qualities make it the main candidate for the future development of optoelectronics and photonics.

Additionally, GaAs is the leading semiconductor of a range of materials : GaAs-based III-V ternary and quaternary alloys. These semiconducors are at the origin of a whole family of optoelectronic devices used for various optical spectral bands, among others in optical fiber telecommunication applications. As will be described below, it is beneficial to photovoltaics in the race towards maximum achievable efficiency, since high efficiency photovoltaics will also make use of the concept of semiconductor material tailoring : adaptation within a family of alloys of the properties of materials to a device requirement.

II. Present status of solar cells for space applications.

In this paragraph and the following text, AM0 refers to Air Mass zero. This indicates conditions of space environment, where the solar light is not absorbed by the atmosphere. Terrestrial conditions will be quantifed by a non nul air mass, typically AM 1.5. On earth, PV terrestrial conversion efficiencies are slightly higher than spatial ones and this is mainly due to the differences in the energy distribution of the solar spectrum.

Today, typical efficiencies of production Si solar cells are around 15% AM0. Considering bare cells (i.e. without coverglass and not mounted on panels), this means that, with the AM0 solar constant of 1.35 kW/m², 5m² are necessary to produce 1 kW of electricity. An efficiency of 30% with alternative cells would

half this figure. The gain is obvious in the case of Megawatt scale power plants.

The highest laboratory efficiency at 25°C reported for Si solar cells is 20.8% AMO [2] using the passivated emitter rear locally diffused (PERL) cell. GaAs solar cells have reached 25.7% under terrestrial conditons [3], to be compared with the corresponding 24% (AM1.5) of the above mentionned PERL cell. Both these results are within ≈ 85% of the theoretical limits at 25°C and are milestones toward future developments.

An important feature of GaAs cells is their increased radiation resistance compared to Si: the GaAs solar cells which power the two Japanese communication satellites CS3 launched in January 1989 (average efficiency 17%) have shown less degradation than their Si counterparts in the 88-89 period [4].

Intrinsically, GaAs can reach potentially much higher efficiencies than Si, in particular at the actual operation temperature of solar panels in space (60-80°C) and this leads to a substantially higher power-to-area ratio. However, an other important figure of merit for space applications is the power-to-mass ratio, and considering the current epitaxial growth technology, this is an important drawback for GaAs compared to Si, since the density of GaAs is 2.5 times higher than that of Si. For example, a bare Si cell, 300 μm-thick with an efficiency of 15% will give a power-to-mass ratio of 290 W/kg. To achieve a similar figure, more than 34% will be required from a GaAs cell of the same thickness. However, one should notice that the III-V compound direct gap semiconductors being highly absorbing materials, the thickness of the active PV part of a GaAs cell is limited to 3-5 μm (about 200-300 μm in Si). Additionally, the price of a GaAs substrate is 5 times higher than that of a Si one.

These figures stress the importance of weight reduction for the GaAs-based cell. Three solutions are being developed, with significant progress achieved recently, namely growth on germanium substrates, on silicon substrate and on reusable GaAs substrates.

Ge has almost the same density as GaAs. However, the much greater fracture toughness of this covalent material[1] renders its thinning less critical than that of GaAs. 87.5 μm thick GaAs/Ge solar cells have shown their handling capabilities [5]. This property added to the adapted lattice parameter and the thermal expansion coefficient match between GaAs and this substrate has made Ge the most developed substitute as an epitaxial substrate for GaAs. Growth on Ge has almost reached the production stage with the GaAs/GaAs production line completely switched over to GaAs/Ge in the United States. 6 x 6 cm², 75 μm-thick GaAs /Ge cells are presently in a well advanced stage development [6]. The widely used technique is the method called MOVPE (Metal-Organic Vapor Phase Epitaxy). Multisubstrate MOVPE machines are available for mass production of III-V compound-based optoelectronic devices and solar cells.

Growth on silicon substrate is an elegant solution, because of the maturity reached by both GaAs and Si : eventually, one can imagine devices which will handsomely mix the optical and electronic properties of both semiconductors in a tandem PV structure. However, GaAs and Si are strongly lattice-mismatched with different values of thermal expansion coefficients. Nevertheless, this has been overcome with filtering techniques for the defects generated at the interface between GaAs and Si, and which affect the efficiency : a value of 18.3% AM0 on a 2 x 2 cm² GaAs on Si cell has been demonstrated recently, Si being a passive substrate in these heteroepitaxial cells [7].

The third technique is the separation of the active layers of the cell (≈ 5 μm) from its substrate, for example through the so-called CLEFT technique. A mini-module fabricated in that way has recently shown a 19.5% AM0 efficiency [8].

Now, what are the best ways of reaching higher conversion efficiciencies ? This can be done by minimizing the intrinsic losses in PV conversion, and/or by increasing the PV voltage of a given cell. To these two approaches correspond respectively spectrum division and concentration.

III. Towards higher efficiencies

The main idea at the basis of the spectrum division concept is to make a photovoltaic conversion of different bands of the solar spectrum by different materials. Calculations show that, for example, the efficiency of a 12-cell system would attain 66% (500 x AM0) [9], reaching a value close to 70% with 24 cells. The first cell facing the sun converts the higher energy photons and transmits the photons

with energies inferior to its bandgap to the following cell, and so on. This is illustrated in figure 3 in the case of 4 cells stacked on top of each other.

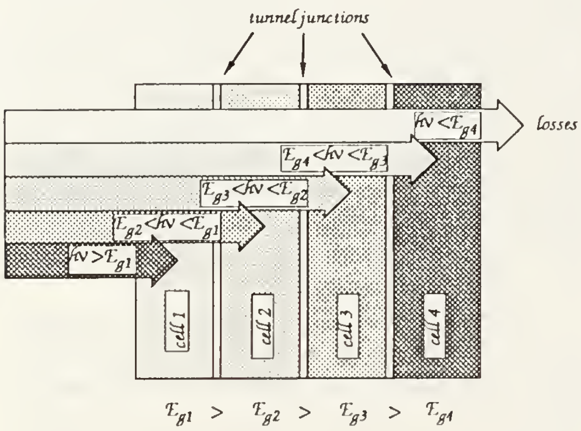

Figure 3. A monolithic stack of 4 cells to achieve quadrispectral PV conversion [10].

III.1. Multispectral conversion.

Cells can be stacked on top of each other either monolithically (the individual elementary cells are grown in the same sequence), or mechanically; in this latter case, the cells are fabricated individually and then stacked : this Mechanically Stacked Multi-Junction Cell tech-nique has demonstrated the highest energy for solar energy conversion : 31% under 100 AM0, using a stacking of two III-V compound-based solar cells (GaAs / GaSb) .

The feasability of concentrator module mounted in "thick" solar panels for terrestrial and space utilizations, based on the assembly of Fresnel lenses (C=100) with the above GaAs/GaSb tandem PV structures, is currently under study [11].

In the case of a monolithic tandem, the connection between the two cells is achieved by different techniques, for example through a tunnel junction. For practical considerations, these monolithic cells are limited at the moment to 2 junction devices : this already requires typically the growth of nine different layers on top of each other. Additionally, two stringent conditions must be fulfilled by monolithic PV cascades : both current and lattice matching. Since the 2 cells are series connected, the current produced by the upper cell must be the same as that produced by the lower cell, leading to a constraint on the bandgap combination. On the other hand, the epitaxy of a monolithic stack imposes a similarity in the crystalline lattice parameters of the two materials and the substrate on which they are to be grown. Although heteroepitaxy has made enormous progress in the past few years - an example being the heteroepitaxy of GaAs on Si, mentioned above - it would be still very critical to deal correctly with more than one mismatched hetero-interface. Despite these technological difficulties, monolithic tandem cells now reach efficiencies higher than single junction devices, the highest reported being 27.3% (AM 1.5) [12].

III.2. Concentration

An other way to increase efficiency is to concentrate light. Concentration results mainly in an augmentation of the open circuit voltage V_{oc} caused by the large increase of the short circuit photocurrent of the cell I_{sc}. The expression of V_{oc} shows a proportionality to the logarithm of the ratio I_{sc}/I_d, I_d being the dark current of the p-n junction.

Figure 4 illustrates the increase in conversion efficiency as a function of the concentration ratio C concerning : a single junction GaAs

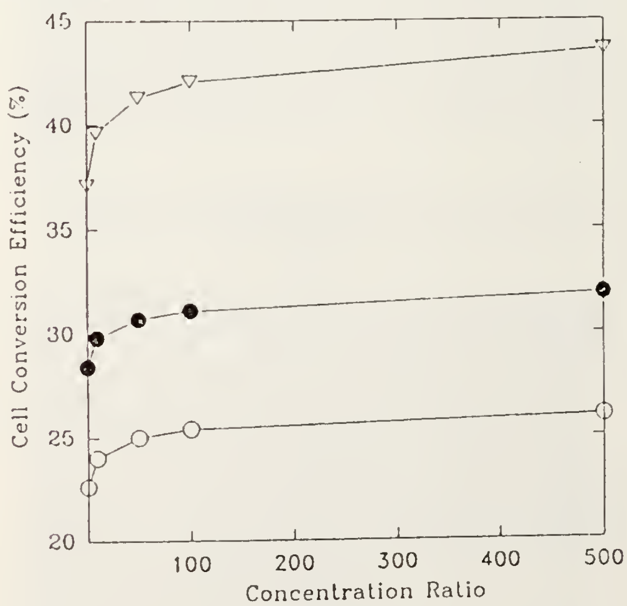

Figure 4 : Calculated influence of concentration ratio on PV conversion efficiency.

o single GaAs cell

• $(GaIn)P_2$ /GaAs tandem

Δ quadrispectral converter described below

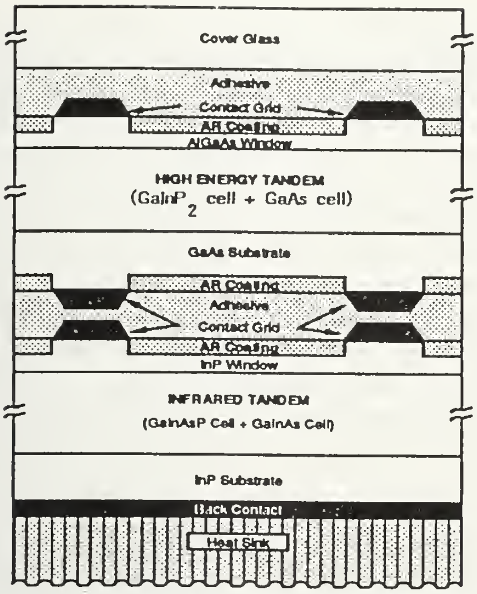

Figure 5 : Schematic cross section of a stacked 4-bandgap PV structure currently developped at LPSES (Rainbow cell Project).

	AMO			
	η ($E_g^{(1)}$ = 1.91 eV)		η ($E_g^{(1)}$ = 2.02 eV)	
C	300K	370K	300K	370K
1	35.1	28.6	37.1	32.2
10	35.7	31.6	39.6	35.4
50	37.3	33.7	41.3	37.6
100	38.1	34.5	42.1	39.6

Table 1 : Projected efficiency in space at 300K and 370K of a quadrispectral PV cell made from 2 stacked monolithic tandems. Top : $(Ga,In)P_2/GaAs$ two-terminal tandem grown on GaAs ; bottom: (Ga,In)As/(Ga,In)(As,P) two-terminal tandem grown grown on InP. ($E_g^{(1)}$ is the bandgap of (Ga,In) P [13, 14]).

cell, the $(Ga,In)P_2/GaAs$ tandem and the quadrispectral converter described below. On can note that the increase in efficiency is rather rapid in the 1<C<100 range. An important side effect of concentration is the substantial cost reduction, arising from the replacement of significant quantities of much more costly semiconductor material, like the III-V compounds, by less costly optical elements. Additionally, silica-based concentrating optics could be very interesting in the case of an eventual future lunar processing plant.

III.3. A realistic project : the quadrispectral conversion.

The above mentioned results show that very high efficiencies are within reach in the next few years, with the combination of the different tandem technologies : for instance, the assembly of two monolithic tandems, mechanically stacked on top of each other (Fig.5) and operated under concentration has been modelled at LPSES [13,14] . As seen on Table 1, this PV structure will permit the achievement of 40% AMO cell efficiency in concentrators operated in space [14]. It should be noted that all the individual components of the quadrispectral cell are now mastered at least at the laboratory scale.

IV. Applicability of high efficiency concepts to powersats and SPS's

IV.1. Specific requirements.

The Powersat network will take place in Low Earth Orbit (LEO), whereas the SPS will be installed in Geostationary Earth Orbit (GEO). An indicative list of the constraints for those two different types of environments is given in Table 2. To this day, the effects of both environments on silicon solar cells are fairly well known [15] . Regarding GaAs, it must be noted that the number of solar cells launched on satellites has increased in the past years, permitting an optimistic in-situ view of the behaviour of this material in space [4, 16, 17].

	LEO	GEO
• Irradiations (equiv. 1 MeV e- for a 10 year mission)	8×10^{13}	10^{15}
• Thermal cycles and period	-80/+80°C 6000 year	-180/+40°C 92/year
• Micrometeorits degradation	-0.5%/year	-0.5%/year
• Atomic oxygen	yes	no

Table 2 : Space environment constraints.

Both powersats and SPS require much higher powers than have ever been installed on satellites : the order of magnitude is 10th of kilowatts for powersats, up to megawatts and gigawatts for SPS's. The immediate issue is the enormous increased size of the array.

Consequently, a very high power-to-area ratio is demanded. It appears that these large sizes would make preferable the utilization of flexible arrays. Therefore, the question is arisen on the compatibility of this kind of array with high efficiency thin III-V compound-based cells described above.

An important feature is the applicability of concentration and multispectral concepts (which should allow the highest power-to-area ratio) to such large arrays in space : one has to design both light and rigid structures for the PV panels. Additionally, both power-sats and SPS's are expected to be long life systems : their anticipated lifetime is 30 years compared to about 10 years for present day existing satellites. This stresses the importance of two points : (i) annealing capabilities in the chosen semiconducting materials; (ii) and/or the low cosmic irradiation degradation expected in the high efficiency multispectral solar cells resulting from their use in high concentration PV modules. These features would permit a very substantial gain on EOL efficiencies of SPS's.

IV.2. Issues and tradeoffs.

Due to their complex epitaxial structure, the multispectral cells described above are expensive devices. In the case of tandems and for compatibility with existing power conditioning designs on spacecraft, two-terminals devices are preferred [18]. The use of concentration allows a much smaller surface of high price semiconducting materials. Additionally, increased efficiency, reduced cell mass and panel area will have an influence on launch costs. Moreover, the added advantage of the concentration option concerns other important aspects such as smaller area exposed and shielding against the space environment. For example, a specific power analysis showed a higher end-of-life ratio for concentrators GaAs/Ge and GaAs/GaAs single cells, due to shielding [19]. However, the use of concentrators brings stringent requirements on the system in terms of sun-tracking, thermo-elastic effects between the different elements of the assembly, electrostatic charging and heat dissipation.

NASA has established that a one-degree tracking error is reasonable for most missions of interest. Tracking errors can be accommodated by a larger cell size which allows a focusing onto a region smaller than the cell active area [20]. For example, no degradation in current output has been measured in the case of the mini-dome Fresnel lens photovoltaic concentrator array when pointed to within ± 1 degree. Up to 4 degrees tracking errors have

	Retractable planar space solar array[20]	Advanced PV concentrator system present-improved [21,22]	Advanced Photovoltaic Solar Array (APSA) [23,25]
• Range of power	10 kW	100 kW	10 kW/wing
• Type of cells	tandem GaAs/Ge	GaAs	GaAs/Ge
• BOL Cell efficiency in percentage	24.4	21.4 - 24	18
• Size (cm^2)	4 x 4	4 mm diameter	2 x 4
• Thickness (μm)	100		80
• Operating temperature (°C)	81	100	≈ 28
• Type of array	rigid	rigid	flexible
• BOL specific area (W/m^2)	304	239 - 281	> 110
• BOL specific power (W/kg)	27.8 - 112.1	75 - 88	> 150
• Remarks	very light concentration through shutters [1,3]	C = [illegible]0C [illegible]ni-dome Fre[illegible] [illegible]s)	flat panel

Table 3 : Overview of space PV array technologies in development using GaAs based solar cells

been analysed in this case and could be tolerated. It should be noted that even flat plate solar panels should be pointed for optimum operation, but in this case with obviously a wider tracking error range.

Table 3 presents an overview of high power array technologies using GaAs-based solar cells. All these arrays require either existing or almost developed technologies.

Provided some drawbacks common to all concentrator systems are overcome, the advanced concentrator system appears applicable to large area, high power space systems in low earth orbit, like a space station providing 300 kW in LEO.

IV.3. Space qualification of high-efficiency photovoltaic components.

Multispectral component solar cells have been tested on the LIPS III experiment [24] and showed compatible rates of decays : this is an important point since, in a multijunction cell, the performance is limited by the most degraded elementary cell. In the various options indicated in Table 3, the cosmic environment compatibility of the various materials used in optics and interconnections is addressed. It appears that further developments are necessary.

V. The monochromatic PV conversion : application to energy transmission in space.

Reducing the spectral bandwidth of the incident photon energy spectrum leads to reach the limiting case of monochromatic photovoltaics, i.e. the intrinsically highest PV conversion efficiencies. If these photons come from a laser beam, it could open the route of the possible very attractive application of energy transmission in space. In this respect, III-V compound semiconductors offer a wide range of suitable materials, both for emission of optical power (laser diode arrays) and its photovoltaic conversion. Since the monochromatic PV conversion efficiency increases with increasing bandgap, one should choose large bandgap materials such as GaAs, (Al,Ga)As or $(Al,Ga,In)_{0.5}P_{0.5}$ (a GaAs lattice-matched alloy) to reach monochromatic conversion efficiencies well above 50%.

A preliminary experiment of remote powering has been achieved at LPSES, which already demonstrates a 52.3% photovoltaic efficiency [26]: a monolithic PV generator has been specially designed to convert the laser light coming from an optical fiber and emitted by a (Al,Ga)As laser diode : this generator can supply a direct voltage of above 5 V in a large range of operating temperatures.

For space applications, in the case of transmission of energy to earth or from space to space, a YAG laser channel is thought to represent one of the suitable demonstrator options. On Figure 1, the vertical lines indicate the wavelengths of the different presently available lasers, suited to maximum transmissibility from earth to space. For the reception of these laser optical radiations, the adapted PV materials are once again found in the III-V compounds family : considering for example the YAG laser line at 1.06 µm, the alloy (Ga,In)(As,P) grown in InP [10], well-known in optical fiber optoelectronics, responds to this demand.

VI. Conclusion.

From the production of electricity in space using solar energy PV conversion, to the transmission and reception of optical power, GaAs-like compounds offer significant advantages. High efficiency conversion devices are now at hand. Multispectral structures have proven assets at the solar cell level in terms of very high conversion efficiency. Their expected advantages include higher specific power or area, when combined with concentrators. For this purpose, a novel very high efficiency multispectral solar cell based on stack assembly of two monolithic tandems has been proposed. These "rainbow" cells are expected to convert solar energy in space concentrator panels with an efficiency around 40%. It should be noticed that large scale fabrication of such small size PV cells might not raise any material availability problem among the industries which are already involved in mass production of III-V semiconductor optoelectronic devices for different type of applications in various optical bands.

Acknowlegdments.

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B3.2 Electronic materials for solar cells

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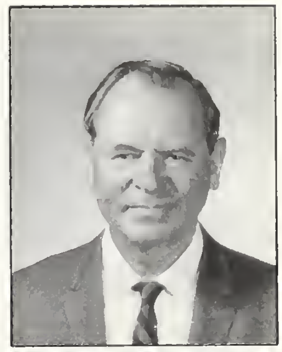


RESUME

Après une brève discussion du problème de l'optimisation du rendement de conversion des cellules solaires, on démontre l'importance d'une grande perfection cristalline. On décrit l'exemple du silicium amorphe et ses difficultés intrinsèques, typiques des matériaux semi-conducteurs amorphes. Enfin, l'utilisation des composés cristallins III V est discutée, à la lumière de leur développement considérable dû aux nouvelles techniques d'épitaxie qui en ont fait l'élément de base de la technologie des dispositifs, et notamment des cellules solaires.

Abstract

After a short description of the problem of optimisation of photovoltaic solar cell efficiency, the importance of crystal perfection is addressed. The case of amorphous silicon and its fundamental difficulties are described which are typical for other amorphous materials.- Finally the III-V compound crystals are discussed and their enormous development due to new epitaxial methods is demonstrated which has become the basis for device technique including solar cells.

A) The Optimization of a Photovoltaic Solar Cell.

The influence of the materials or crystals is all-decisive for the properties of photovoltaic cells. The drive for higher efficiency is an economical "must" if solar cells should become competitive with other energy generators. A 20 % solar cell can cost seven times as much as a 10 % cell and still be competitive.There are mediocre and good materials but also excellent ones for solar cells.

To understand the influence of the crystal type on the working of a PV-cell, we consider first how such a cell has to be optimised.

Fig.1

Schematic of a typical solar cell.

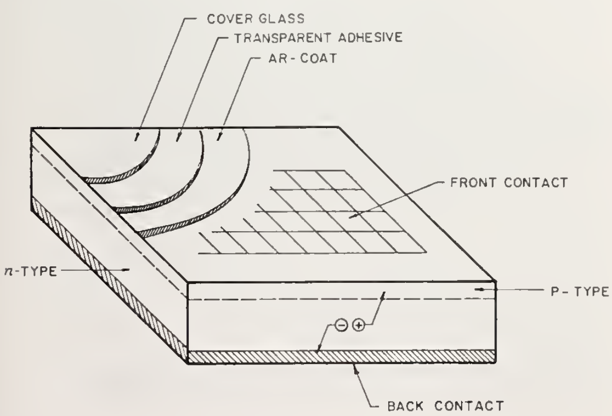


Fig.1 shows schematically the structure of a solar cell. From the cover glass to the back-side contact, all parameters enter into the final efficiency product of I_{sc} (short circuit current), V_{oc} (open circuit voltage) and FF (filling factor).

Conditions for optimization of

$$\eta = I_{sc} \times V_{oc} \times FF$$

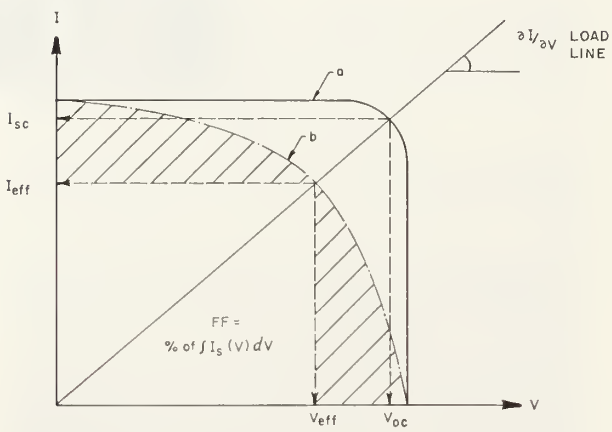
are discussed along the lines:

1. device geometry
2. Optical properties (absorption, reflection,transmission)
3. Materials (crystal perfection,carrier lifetime, charge separation,junction quality or abruptness, conductivity and contact quality)

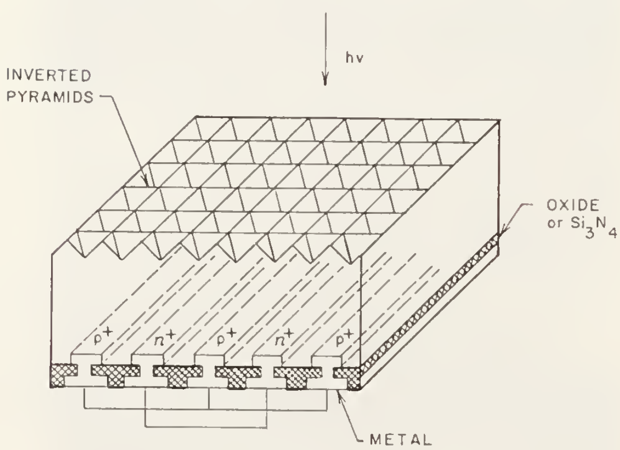
A high value of I_{sc} depends on: a strongly absorbing top-layer (minimized reflection) by application of double AR-coatings (Titanium/Tantalum oxides, SiO_2 or Si_3N_4), high semiconductor surface conductance and dense contact grids. Also, thin and abrupt top junctions, base-layer thick anough to offer sufficient carrier absorption cross section but thin enough for the prevailing carrier-lifetime to enable minorities to reach the junction (e.g. holes to reach the top p^+-layer are important.)

V_{oc} depends basically on the band-gap value of the semiconductor.Its full value also depends on the junction quality (ideality factor), the recombination velocity S (reduced by surface passivation) and the defect density.

FF, the filling factor depends mainly on the dopant level (conductivity), the contact grid structure (shadowing) and the base-layer degeneracy.
A typical solar cell characteristics is shown in Fig.2
Solar Cell Characteristics.
a: good quality cell with high FF
b: low efficiency cell



Recently much progress was made towards higher efficiency due to the use of interdigitated contact pattern (n^+/p^+) on the back-side (no shadowing) and by grooved (structure etched) surfaces.
Fig.3
Newer form of high-efficiency silicon solar cell with light-trapping surface structure-etch, surface oxidation and interdigitated p^+/n^+ backside junction.



Here an important point is reduced surface recombination, achieved by a complete passivation of the cell surface. [1] [2] - In the case of concentration, the efficiency increases from its AM 1-value (23 %) to 28 %. (100 suns)
In this case one has to consider the thermal sensitivity of the material which is higher for silicon than for the III-V-compounds.

B) Silicon Monocrystals versus Polycrystals.

What does crystal perfection mean for a solar cell?
As in most other devices, high electron mobility and long minority carrier - lifetime or diffusion-length make the device design easier e.g. with respect to contact spacing.- Imperfections in the form of defects and especially grain-boundaries have strong effects on carrier transport.- This is seen in a general way by considering the electron-wave package. In a regular lattice it is expressed by the known Bloch-wave-function with a time-dependent part:

$$A\, e^{i\omega t} \quad \text{(Amplitude)}$$

and a position-dependent part:

$$e^{-2\pi i(a\cdot r)}$$

where a = 1/d = reciprocal lattice cell length or geometrical lieu for Bragg-reflections.
The Bloch wave:

$$\emptyset = A(r)\, e^{2\pi i[\nu t - (a\cdot r)]}$$

can be disturbed when deviations from periodicity occur. Bragg reflections are then changed and

$$a(r) = a(r) + \varepsilon\, a(r)$$

which means that transport properties of the crystal change. This can also be demonstrated by a change in the wave-vector domain or the Brillouin-zone. [3] One can show that such changes occur already due to a line of vacancies in an otherwise perfect crystal. [4]
If however defects, like dislocations are introduced, the space charge around these and the attendant lattice strain with dilatation, cause even stronger effects. Edge dislocations cause disrupted bonds with a strong affinity for free carriers and impurity ions. They also result in lattice deformations. Around the "dangling-bond" compression- and dilatation zones form with corresponding band-gap changes.

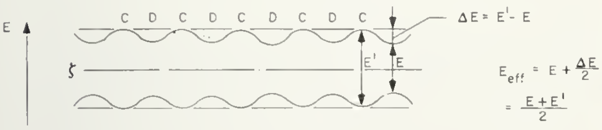
Fig.4

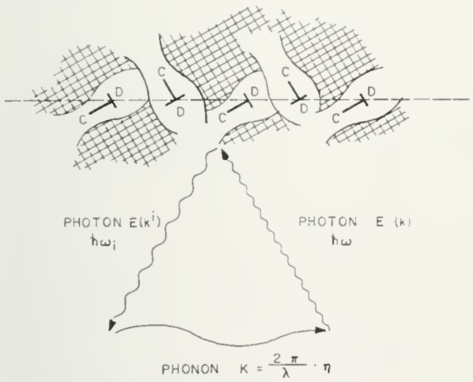
Band structure changes along a dislocation line with compression (C) and dilatation (D) points around the edge-dislocations. Band gap changes are periodic with an effective band energy:

$$E_{eff} - E + \Delta E/2 = (E + E')/2$$

The injection of a photon of wave-vector k and frequency ω , may result in an inversion lowering at the dislocation and emission of a photon of frequency ω_i and wave vector k'. In the indirect semiconductor, energy balance is established by a phonon of wave vector K. In a deformed lattice there are numerous possibilities to supply such a "pseudomomentum" vector $K = 2\pi n/\lambda$
λ = De Broglie wave length.
If such dangling bonds are lined up as is the case in grain-boundaries, they cause p-n-p (n-p-n) barriers in the crystal, reduce current flow and thus mobility and lifetime. In addition such zones are the sites of strong recombination. They not only cause electrons to be captured by a dangling bond acceptor state but they also can thermalize incoming photons. What is meant by this can be seen from Fig.4.- An incoming photon with wave vector k undergoes a transition. The inelastic scattering

of a photon ($k \rightarrow k'$) is balanced by the pseudomomentum vector K of a lattice phonon: $K = n\, 2\pi / \lambda$ $(n = 1,2,3....)$ with λ fulfilling the energy balance. Additionally, thermionic field emission has been shown to contribute to the interface generation-recombination process. [5]

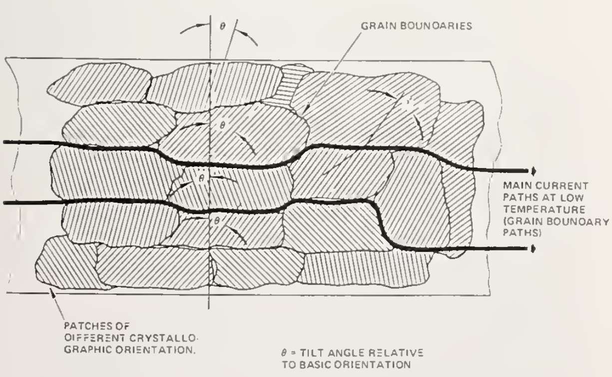




In polycristalline silicon (and also in the other semiconductors) one has a multitude of grains and thus grain-boundaries. However, the majority of these are twins or twin-like structures. Their influence on mobility and life-time is of minor importance. [4]
In the case of grain boundaries with edge dislocations however, longitudinal conduction along those boundaries may cause current-flow lines to follow the boundaries.

Fig.5

Grain Boundaries between grains are not only forming space charge barriers vertically to the boundaries but are also conducting preferably along the overlapping dangling bond states within the boundaries.



In polycrystalline silicon and in silicon on sapphire such grain boundaries are rare. The majority of Defects are twin-like structures with a minor electrical effect on carrier transport.

Fig.6

shows an electron micrograph of a polycrystalline silicon film on sapphire, made by CVD. It shows the typical twins but only very few grain boundaries. This is the reason for the relatively minor losses in poly-material as compared to monocrystals.

Much work was done to assess the importance of these defects for solar cell performance. [6] It turned out that polycrystalline blocks can be made into useful solar cells of 17 % efficiency and that a sophisticated interconnection technique can yield modul efficiencies of over 14 %. [7]
Schemes have even been worked out to use grain boundary layers as additional photoelectrically sensitive zones and as a preferred conductor to enhance the efficiency of polycrystalline solar cells. [8]

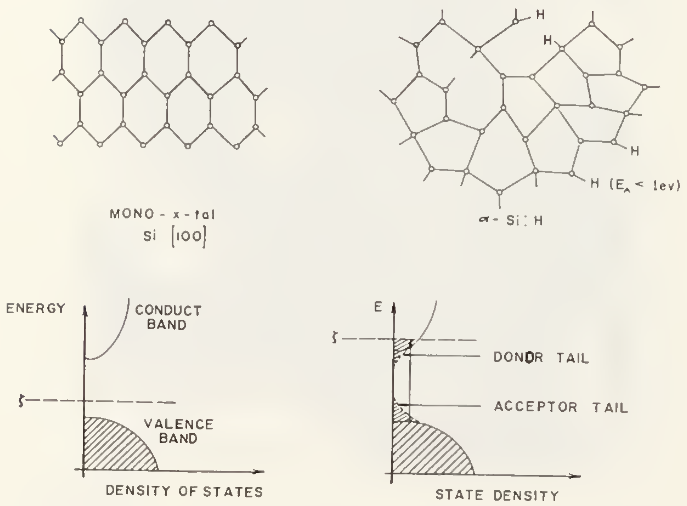
C) Amorphous Silicon: α-Si:H and other amorphous crystals.

The use of amorphous silicon has been prompted by the search for cheaper base material. Simple flame-fusion and deposition from halides has resulted in usable silicon films. While lifetime and mobility are extremely low, contacting is achieved by transparent conductors like ITO (Indium-Tin-Oxide).
The originally low efficiencies of 5 to 6 % have been improved by the use of heterojunctions of the type
α- Si,C:H/ α -Si:H and by addition of intrinsic layers. But even at η -values of 10 % and above, these

cells cannot really compete with mono- and poly-crystalline based cells as they suffer from inherent instability. (the Staebler-Wronski-Effect) Their ultimate efficiency is moreover limited due to the fact that the miniature crystallites or microcrystals have to be connected by the transparent-conducting layer which keeps FF, the filling factor, in the 70 % range and below due to limited conductivity.The problems with such amorphous structures stem from the deformed lattice.

Fig.7

Difference between a monocrystal and amorphous structures. The band-structure of the α-Si:H-film shows extended tail-states in both, the valence and conduction bands. The hydrogen-silicon bond (saturation of dangling bond levels) has a low activation energy. ($<$ 0,1 eV)



In the above figure we have compared the band structure of a monocrystal with the one of an amorphous crystal. The difference between monocrystalline and amorphous material is the absence of regularity or periodicity of bond distance and bond saturation in the latter. There are also many dangling bonds (an average of 10^{18} cm^{-3}.) Therefore band tail-states are created. Transitions occur from band-tail-states into the conduction band. Many properties of this material are known from research on the innermost core of the grain boundaries. (compare Fig.4)

Here the dangling bonds, measurable by ESR (electron spin resonance), and strained and deformed bonds are distributed at random over the whole material. The saturation of the dangling bonds by hydrogen atoms is a well-known method to improve the material properties, especially lifetime and mobility. But the activation energy of a Si-H-bond is very low, below 0.1 eV, and such bonds as well as Si-Si-bonds in amorphous silicon can be disrupted at relatively low temperature. (a few hundred degrees C) and also by IR-light injection.

The "Staebler-Wronski" effect of aging has never been eliminated. A somewhat improved stability can be achieved by multi-junction devices with strong nitrogen doping. But some of the remedial measures, like multilayers and p/i/n-layers increase the production costs of these cells considerably.

Other amorphous materials used are CdTe (1.44 eV) and compounds like $CuInSe_2$.

Such II-VI-type compounds are chemically not as stable as the III-V-compounds and in amorphous form they suffer from similar instabilities. CdTe is also difficult to contact (low FF) because of film-degradation.Here also, the addition of an intrinsic layer has improved the stability somewhat. Films like:

ZnTe(p)/CdTe(i)/CdS(n) have produced efficiencies in the 7 to 11 % range.

$CuInSe_2$ was improved by the addition of Gallium. Usually tandem-cells like α-Si:H/$CuInSe_2$ or ZnO/CdTe/$CuInSe_2$ and also ZnO/CdZnS/$CuInGaSe_2$ yield better efficiency values. (10 to 12%) All those mixed compounds with copper and sulfur, suffer from the fact that Cu-diffusion and Se- and S-compound instability play a major role especially at higher temperature.

The epitaxy is also a problem when no crystal orientation is fixed and deposition on amorphous substrates will cause formation of non-isomorphic deposits.

D) III-V (II-VI) Compound Crystals.

In the development of the III-V-type solar cells in particular, one sees a history of constantly increased efficiencies especially since multilayer CVD (chemical vapor deposition) has been developed.

In this technique one has a natural way to adapt one compound to another by a gradual change in stoichiometry, starting with a monocrystalline substrate. In this fashion one has the possibility to

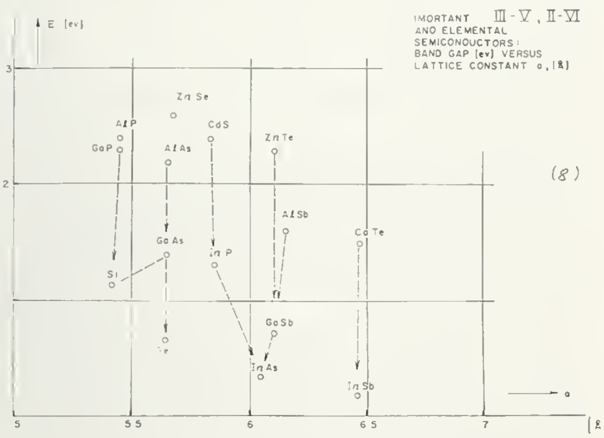
a. improve crystalline perfection due to lateral outgrowth of dislocations
b. adapt materials with different lattice constants to one another by admixing-in ternary and quaterny compounds
c. combine different bandgap crystals and produce abrupt p/n-junctions.

Fig.8

Band-gap energy versus lattice constant for important III-V and II-VI and some elemental semiconductors.

Here we see the interesting cases of AlAs-GaAs-Ge where the lattice constant varies only in the second decimal (Ge: 5.64 Å ; AlAs: 5.63 Å and GaAs: 5.65 Å)
Other interesting cases of matching couples are AlP-GaP-Si and AlSb-GaSb. With II-VI-compounds, a few matching pairs are apparent: CdTe-InSb for instance.- We see clearly why III-V-compounds dominate also in other fields

like microcircuitry, optoelectronics, encoding, microwave IC's and others.

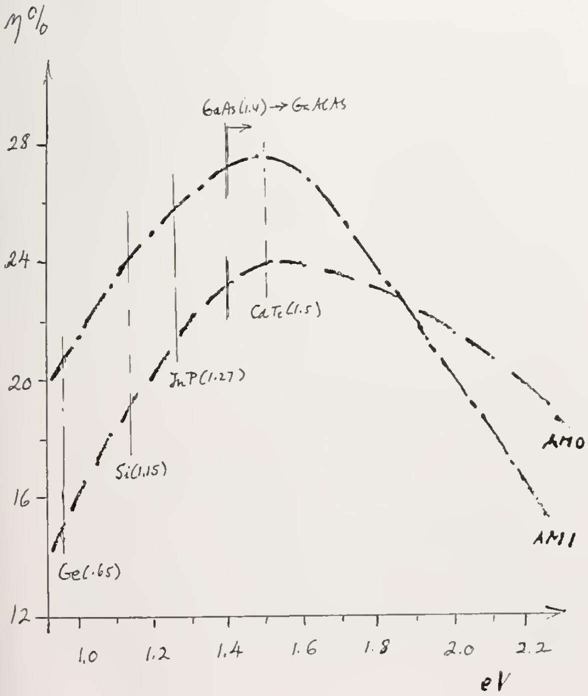


For solar cells it is obvious that cheaper silicon cells will find application where less direct solar energy must be converted as e.g. in roof-top moduls, in trailor-type supply packages and in gadgets like pocket computers etc.

If however large-scale power plants are the object, we will see a steady development toward high-efficiency III-V-solar cells in concentrator moduls where the solar rays are collected by optical means (not by large size solar cells) and where relatively small but highly efficient cells convert the photon flux with a better than 30 % efficiency.

Fig.9

Here the 1 sun (AM 1 and AM o) conversion efficiencies for the different bandgap semiconductors are plotted. GaAs respectively GaAlAs and CdTe are near the top in efficiency.



An important reason to prefer III-V-compound cells in solar concentrators is the temperature coefficient which is more favorable than in silicon. In such systems it is desirable to also utilize the IR-portion of the spectrum by the use of heat-conversion devices (stirling engines in a Carnot-cycle e.g.) and to use temperatures near or above the 100°C range. While silicon cells decrease in efficiency to 1/2 of the room-temperature value when reaching 100 C, III-V-cells of the GaAs-type decrease only for some 12 % at 200 suns concentration. This point was recognized early when different cells were compared under concentratd light. [10] [11]

From the early 20 % efficiency (1975) with GaAlAs/GaAs heterojunction solar concentrator cells, a steady increase was achieved due to newer epitaxial methods and improved layer quality at multiple layer growth. [12]

While monocrystalline silicon solar cells have advanced to over 23 % [1] [2] and modul efficiencies have achieved 17 % [7] , latest values of III-V-tandem cells are in the 35 % range. [13]

To fully utilize the solar spectrum one has to combine several semiconductors with decreasing band gap from the top-layer. This is apparent when one considers the solar spectrum and the relative sensitivity of different band-gap materials.

Full utilization of the solar spectrum is only possible with a combination of cells of different band gap plus a thermal converter for the far IR-portion of the spectrum. The upper cell or cells must have higher band gap and be sufficiently transparent in the frequency - range of the lower cell or cells. In addition the contacting between these cells must be as lossless as feasible. These two conditions are not easy to combine. The higher the number of layers the more complex the contacting. There is a limit to the number of layers in view of the contacting losses.

The solar spectrum can be covered by a multitude of heteropolar crystal combinations. Mostly the upper cell has a band gap between 1.2 and 1.8 eV and the lower cell is in the 0,7 to 1.5 eV - range. For instance: GaAs (1.45 eV)/ Si (1.15 eV) or GaAs/Ge with Ge: 0.75 eV. In the case of GaAs on Si one has a problem with both, lattice constants and the thermal expansion coefficient. (see under "epitaxy")

Important pairs for epitaxy are:
GaAs(1.45 eV), d=5.65 Å (Angstrom) / Ge (.75 eV) ,d=5.646

GaP(2.2 eV), d=5.44/Si(1.15 eV),d:5.42
AlAs(2.15eV),d=5.661/GaAs; d:5.653
AlSb(1.65 eV),d=6.135/GaSb(.73eV) d: 6.095 Å

In addition, ternary compounds like GaAs/GaInAs or GaAlAs/GaInAs or GaInAsP/GaInAs play an increasing role. In this case one can better tailor gap energies and lattice constant match. These combinations are of great importance also in MMIC (microwave and millimeter wave microcircuitry) and in integrated

optics in connection with the coming huge application in fiber-optic communications world-wide.

While GaAs PV-cells have reached efficiencies of 24.3 % (AM1) and 29.2 % at 100 suns concentration, higher efficiencies are feasible, especially with tandem-cells.

In this case there are two ways to interconnect the cells in series:

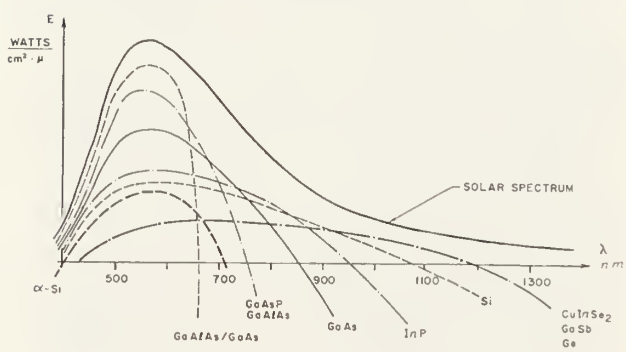
a) by internal connections e.g. using tunnel-diode connections or metallized grooves.
b) by external connections.

So far, internal connections have shown some problems. Higher efficiency was achieved with external connections.

There are more complex forms of tandem cells [14] [15] , which,when used in combination with concentrators and heat engines, can yield overall efficiencies close to the 50 % mark. [16]

Fig.10

Solar Spectrum versus wavelength and energy portions convertible with the different semiconductors.



The typical layer sequence of a high-efficiency cell is e.g.

Top cell	n^+-$Al_{.9}Ga_{.1}As$
	n^+-$Al_{.3}Ga_{.7}As$
	p -$Al_{.3}Ga_{.7}As$
tunnel junct.	p^{++} GaAs
	n^{++} GaAs
	or
	n^+-$Al_{.9}Ga_{.1}As$
	n^+-$Al_{.4}Ga_{.6}As$
	p -$Al_{.4}Ga_{.6}As$
	p^+ - $Al_xGa_{1-x}As$
	p^{++}- $GaAs/_{n}{}^{++}$ -GaAs
	n - $Al_xGa_{1-x}As$

with a bottom cell: n^+/p GaAs or n^{++}/p^+ GaAs

substrate: GaAs

Dopant concentration is approximately 10^{17} cm^{-3} for the n-type GaAs and 10^{19} cm^{-3} for the p^{++} GaAs.

Ultimate efficiencies are 34 to 35 % at AM 1 and 37 % for 100 suns concentration.

E) Epitaxial Methods.

There has been enormous progress in the field of epitaxy since the early days of LPE (liquid phase epitaxy) which initiated the work on the famous heterojunction GaAlAs/GaAs for LED's and related devices.

We have seen a steady variation from the original ALE (atomic layer epitaxy) and CVD (chemical vapor deposition) to more elaborate methods like very high vacuum deposition i.e. MBE (molecular beam epitaxy).- As the chemical methods developed in parallel with the ultra-high vacuum methods, it became clear that even the best vacuum methods had a problem with the interface purity and that molecular species grow less perfect on a free surface than is possible with reactive gases and organic compounds. (heterogeneous nucleation on a catalyst surface)

For a time the methods of MBE and MOCVD (see Appendix for different methods in epitaxy) seemed to be in competition. MBE achieved abrupt junctions while MOCVD outperformed MBE with respect to layer perfection and showed a better production potential.

With the advent of CBE (chemical beam epitaxy) however, the disadvantage of the very high vacuum condition in MBE (10^{-12} Torr range) and the disadvantage of the gas-flow inertia in MOCVD (less controllable interface abruptness) even with LPMOCVD (low pressure MOCVD),are both eliminated and excellent layer-thickness-control is combined with abruptness and crystal perfection.

The growth of epitaxial layers has resulted in a constant improvement of layer perfection.This especially due to the possibility of a gradual addition of one element to a ternary compound.

This is seen immediately from the dislocation density:

Let the lattice constant of the substrate be a_o and the lattice constant of the growing compound be a_o' then the lattice mismatch ε is:

$$\varepsilon = \Delta a/a_o \text{ with } \Delta a = a_o - a_o'$$

or: $$\varepsilon = (a_o - a_o')/ a_o$$

The linear dislocation distance is

$d = a_{uvw}/\varepsilon$ where a_{uvw} is the lattice translation vector.

a_{uvw} may be equated to a_o in edge dislocations. (Burgers vector)

Therefore the dislocation density 1/d (linear) can be expressed as:

$1/d = \Delta a/a_o^2$ and the area density is

$$N_\Delta [cm^{-2}] = (\frac{1}{d})^2 = \Delta a^2/a_o^4$$

If we express a_o in Angstrom units:

$$N_\Delta \, cm^{-2} = (\delta^2/a_o^2) \times 10^{16}$$

As an example let us use the ternary compound $GaAs_{1-x}P_x$ i.e. the gradual transition from GaAs to $GaAs_{1-x}P_x$.

The lattice constants are:

GaAs: $a_o = 5.654$
GaP $a_o = 5.441$

$\Delta a = 0.213$ and $\delta = 3.76 \times 10^{-2}$

The dislocation density for a non-gradual epitaxy is thus

$$N_\Delta = 4.4 \times 10^{11} \quad cm^{-2}$$

Epitaxy allows for a gradual increase of x in $GaAs_{1-x}P_x$ or a gradual admixing of phosphorous.
If the gradual concentration change per thickness y is:

$\Delta c/\Delta y$ in %

we have:

$$N_\Delta \, cm^{-2} - \frac{\delta^2}{a_o^2}(\frac{\Delta c}{\Delta y})^2 \times 10^{16} \quad \text{or}$$

$$N_\Delta \, cm^{-2} = \frac{\Delta a^2}{a_o^4} (\frac{\Delta c}{\Delta y})^2 \times 10^{16}$$

Thus it is seen that for a gradual admixture of P in the 10 % range, N_Δ will be reduced to

$N_\Delta \simeq 4.4 \times 10^9 \, cm^{-2}$ and lower values for smaller percentages. [16][17]

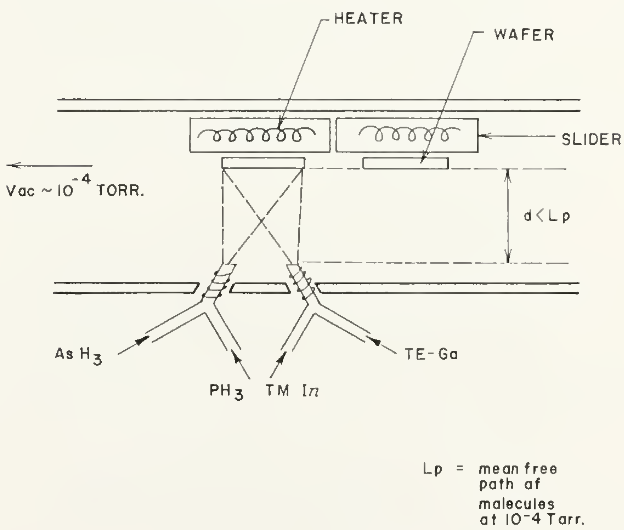
As new epitaxial methods were developed there have been numerous attempts to grow GaAs and GaP directly on monocrystalline substrates. While germanium is a good substrate for GaAs-films as a consequence of a very small lattice misfit of 4×10^{-3}, the growth on silicon is a problem. The lattice difference with GaAs is over 20%. But even for GaP with a small misfit of 2 %, the difference of the thermal expansion coefficients is cause for strain and dislocations. Newer methods have lead to a better control of the interface purity and the dopant gradient. An important step was the application of chemical bond-flipping or heterogeneous catalysis by the use of metal-organic compounds in connection with MBE, leading to MOMBE. Such methods have much improved the early attempts and deposition of GaAs on silicon as well as GaP/Si has resulted in better film perfection. [17][18]

A decisive step was the introduction of chemical beam epitaxy. (CBE)
CBE grew out from MOCVD. It is an important combination of the good interface control in MBE with the chemical (catalytic) action in MOCVD. (see Appendix)

CBE works at a higher pressure than MBE and is very economical in its use of the high-purity gases like AsH_3, PH_3 or TM-In (trimethyl Indium) and TE-Ga (triethylene Gallium). These organometallic gases are blown through heated tubes (crackers) into a 10^{-4} Vacuum chamber and hit directly the substrate surface.

Fig.11

Schematic of CBE.



Due to the fact that the mean free-path of the gas molecules is kept larger than the gas-orifice distance to the substrate, abrupt p/n-changes and clean interface conditions are feasible.
A process described as MEMOCVD or MECBE (migration enhanced MOCVD or CBE) is particularly useful for the deposition of GaAs on silicon substrates.
In this case the initial deposition of a Gallium (or Indium)-layer enhances the molecular mobility during the first nucleation steps. The process is germane to LPE inasmuch as one starts with a non-equilibrium phase of nucleation. [19]

There is no doubt that epitaxial methods will develop further and that steps will be taken to adapt these methods ultimately to the requirements of mass-production, especially important for solar PV-cells.

ppendix.

Short explanation of the different epitaxial processes.

ALE (Atomic Layer Epitaxy)

General description of a depositi-on of elemental constituents and dopants in Angstrom thickness, with or without substrate heating or annealing steps.

LPE (liquid phase epitaxy)

Method to work with liquid metals in which dopants and other constituants are dissolved such that a saturated solution in contact with a monocrystalline surface forms a new monocrystalline layer of the desired stoichiometry and doping.

CVD (chemical vapor deposition)

Deposition by means of reactive gases like SiH_4 onto cold or heated substrates.

VCE (vacuum chemical epitaxy)

Generally a method in which one or more layers are deposited on a substrate through the vapor phase of the basic constituents of the new layers, either at a high or a low vacuum onto a heated substrate.

MOCVD (metal organic chemical vapor deposition)

Use of organic metal compounds like the trimethyls(TM)of Ga,Zn, In etc.metals or the triethylens (TE) of the metals. Generally evaporation in vacuo at some 10^{-3} Torr to 1 atm.

LPMOCVD (low pressure MOCVD)

As above but at a higher vacuum and at lower gas flow rates. 10^{-4} to 10^{-6} Torr.

MBE (Molecular beam epitaxy)

High-vacuum evaporation of elemental constituants to form semiconductors of special stoichiometry and doping on a heated substrate. Vacuum: 10^{-9} to 10^{-12} Torr

MOMBE (metal-organic MBE)

Organic compounds of the metals are used instead of the evaporation of elemental metals as in MOCVD.

ME-MBE (migration enhanced MBE)

Elemental layers of the metallic compounds like Ga or In are first deposited to enhance surface mobility before other components like As or P are added.

ME-MOCVD (migration enhanced MOCVD)

Procedure as above but during the process of MOCVD

CBE (Chemical beam epitaxy)

Newest and most versatile method where TM-In or TM-Ga e.g. are intro duced together with AsH_3 or PH_3 into the vacuum chamber, hitting the heated substrate where thermal pyrolysis takes place instead of kinetic adhesion like in MBE or a pyrolysis with a stagnant boundary layer as in MOCVD.
The advantage: Less waste of expensive high-purity Alkyls (TMGa, TE-In etc.) and no boundary layer. Abrupt doping changes possible. Average vacuum 10^{-3} to 10^{-4} T.

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B3.3 Radiation-resistant high-efficiency concentrator solar cells for SPS

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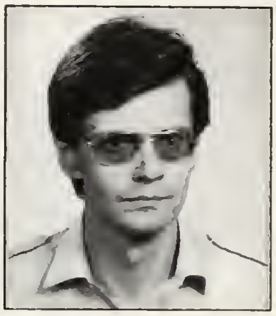

ABSTRACT

An influence of the radiation-resistant concentrator solar cells on performance of the SPS is investigated in this report. Solar cell of the solar power station should survive spiraling through the Van Allen belts and subsequently it should work 25-30 years in GEO without substantial radiation damage ($\Delta P < 10\%$). Radiation-resistant concentrator solar cells can solve this problem.

RESUME

L'influence des cellules solaires à concentration résistantes aux irradiations sur les performances des SPS est étudiée. Les cellules solaires doivent supporter le passage à travers les ceintures de Van Allen et fonctionner ensuite pendant 25 à 30 ans en orbite géostationnaire sans dégradations substantielles dues aux irradiations (DP < 10 %). Les cellules solaires à concentration et résistantes aux irradiations permettent de résoudre ce problème.

Introduction

Up to now solar cells in orbit are protected against radiation only passively by use of glass shields which intercept low energy electrons and protons. This passive protection can never quite suppress the radiation damage.

Active annealing of radiation defects can further improve radiation resistance of solar cells. Standard high temperature (400°C) annealing, however, can't be used for in-orbit anneling.

Athermal photon-induced laser annealing of silicon solar cells was described for the first time five years ago [1]. This result stimulated a study of the photon-induced self-annealing in concentrator solar cells.

Self-annealing of the radiation damage in silicon concentrator solar cells has been measured in our laboratory [2]. The annealing is a nonthermal phenomenon in these experiments. Photon-induced coherent recombination enhanced annealing can explain this phenomenon [3,4].

Self-annealing of the radiation damage in solar cells

Substantial part of the low dose ($1.10^{13}/cm^2$ ~3 MeV electrons) radiation damage in silicon solar cells has been successfully annealed by 100 x concentrated one sun (AM 1.5; 10 W/cm^2) photon beam at low temperature (60°C) in our laboratory [2].

Current density $i_S = 2.1$ A/cm^2 corresponds to this photon beam power density. Recovery in short-circuit current (65%) and in open circuit voltage (30%) has been observed (see Fig.1). Onset of the annealing occurs by current densities $i_S > 1$ A/cm^2 (see Fig.2).

According to analysis [5] of published results of the recombination-enhanced annealing of radiation defects in Si [1,6] , GaAs [7] and InP [8] solar cells, the photon-induced self-annealing of concentrator solar cells is equivalent to forward bias annealing. Forward bias current densities i_F necessary for the recombination annealing agree very well with photon-induced current densities i_S necessary for the annealing. Forward bias

annealing has been measured in most of the semiconductor materials (e.g. GaP [9], Si [10], InP [11], GaAs [12], GaAsP [13] etc.). Therefore, the photon induced self-annealing effect in concentrator solar cells can be of general validity. Photon beam power density necessary for reconbination annealing will be, however, different in different semiconductor materials.

Data on recombination enhanced annealing of the radiation damage in Si, GaAs and InP solar cells as well as results of photon-induced self-annealing of the radiation damage in Si and InP ones summarized in Table 1. supports this hypothesis.

Photon-induced self-annealing of the radiation damage in GaAs solar cells is studied now. Expected values of both photon-induced current density i_S and power density P_S of the photon beam neccessary for self-annealing are included in Table 1. Results of this experiment will be published as soon as possible to compare agreement with expected values.

Athermal annealing is, however, effective only by annealing of the low radiation dose damage. By low radiation doses (in our experiments 1.10^{13} e cm^{-2}) only point defects are created in crystalline lattice. By higher radiation doses (10^{15}- 10^{16} e cm^{-2}), however, point defects tend to create defect clusters or even dislocation loops which are difficult to anneal athermaly. Simultaneous annealing of the radiation damage in concentrator solar cells prevents coalescence of the point defects to more complex ones.

Concentrator solar cells are not annealed during an eclipse. Even at orbits with highest radiation fluence (h~10.000 km, $\Phi_e \sim 10^9$ $cm^{-2}s^{-1}$), however, this period (30min.) is negligible in comparison with the annealing time (600 min.) between eclipses. Very low equivalent 1MeV electron dose ϕ_e [cm^{-2}] $=10^{12}$ damages solar cells during the eclipse.

The radiation damage of concentrator solar cells during the eclipse can be further decreased by use of "thick" (~500μm) coverglases (mass penalty is negligible in case of concentrator cells).

Aplication for SPS

In most of SPS related reports presented to date radiation damage of solar cells was not investigated in detail.

Solar cell of the solar power station should survive tranfer through the Van Allen belts and subsequently it should work 25-30 years in GEO without substantial radiation damage (Δ P < 10%). Corresponding equivalent radiation dose of this mission is ~1.10^{16} 1MeV e/cm^2. Nonconcentrator solar cells can't fulfill this demand. Conventional silicon solar arrays of the SPS spiraling-up to geostationary orbit through the Earth radiation belts will lose of about 23% of their power [14].

Radiation-resistant high-efficiency concentrator solar cells can solve this problem. By use of concentrator solar cells the decrease of power should be less than 10%.

In most of the annealing experiments presented to date the end of life (EOL) radiation doses (10^{15}-10^{16} cm^{-2} 1 MeV electrons) have been used to damage solar cells. There is no practical need, however, to anneal solar cells at the end of life of the satellite. Radiation damage in concentrator solar cells is, under concentrated sunlight, simultaneously annealed. Therefore, it is possible to keep the power level of the solar cells at the highest possible value all the time of the active life of the satellite (See Fig. 3). The self-annealing effect should be included in all calculations of future SPS projects.

The majority of solar cells operate with higher efficiencies under concentrated sunlight [15]. Tandem concentrator solar cells (Si+GaAs, GaSb+GaAs) achieved efficiency above 30% [16] (more than 35% efficient tandem should be available very soon). This fact together with the enhanced radiation resistance of concentrator solar cells can double or even triple the EOL performance of concentrator solar arrays in comparison with nonconcentrator ones.

In early 1980s BOL conversion efficiency of radiation resistant Si solar cells for SPS was 12-14%. EOL ($\Phi=1.10^{16}$ 1 MeV e/cm^2) efficiency of these solar cells would be 8-11%. The author proposes ~30% (EOL) efficient tandem Si+GaAs concentrator solar cells for SPS at present (See Fig. 4.). More than 40% efficient multispectral tandem solar cells can be developed in near future.

Conclusion

Generalization of the self-annealing effect in monocrystalline concentrator solar cells is suggested in this report. This effect should be verified in new multispectral solar cells (GaInAsP, GaAsP, GaInP etc.). The effect should be considered in all space missions where radiation damage in monocrystalline concentrator solar cells is expected.

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Table 1. Injection current density necessary for both forward-bias and photon-induced annealing of the radiation damage in solar cells.

	forward bias annealing			photon-induced annealing			
Solar cell	E_e [eV]	ϕ_e [cm^{-2}]	i_F [A/cm^2]	E_e [eV]	ϕ_e [cm^{-2}]	i_S [A/cm^2]	P_S [W/cm^2]
Si	10^5 rad		5.00 [3]	3.10^6	1.10^{13}	2.10	10.0(AM1.5) [1]
GaAs	1.10^6	1.10^{15}	1.90 [4]	3.10^6	1.10^{13}	<2.00*	<7.00(AM1.5)*
InP	1.10^6	7.10^{15}	0.01 [5]	1.10^6	4.10^{15}	0.02	0.10(AM1.5) [5]

* Theoretical values

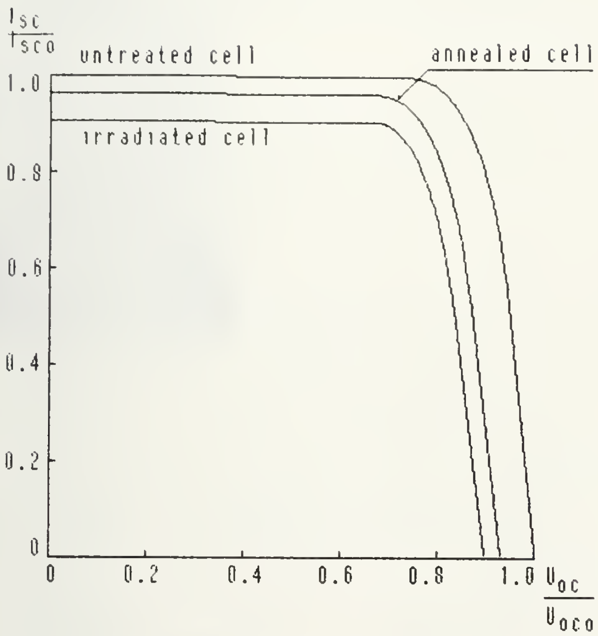

Fig. 1. Current-voltage characteristics of the silicon concentrator solar cell under AM 1.5 spectrum.

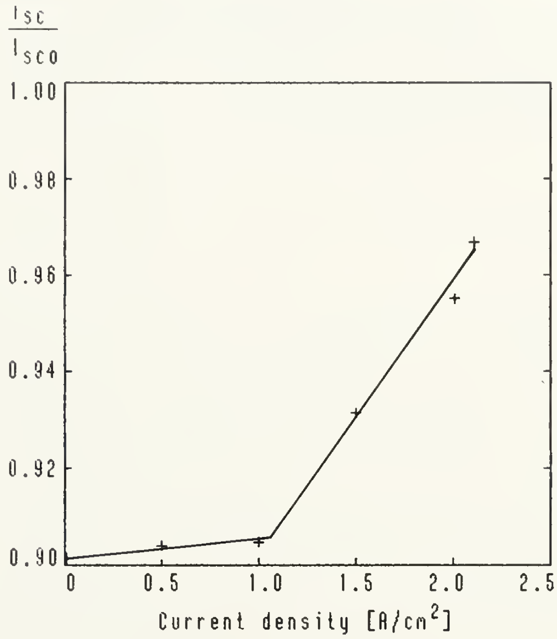

Fig. 2. Recovery of the short circuit current of the Si concentrator solar cells vs. annealing current density

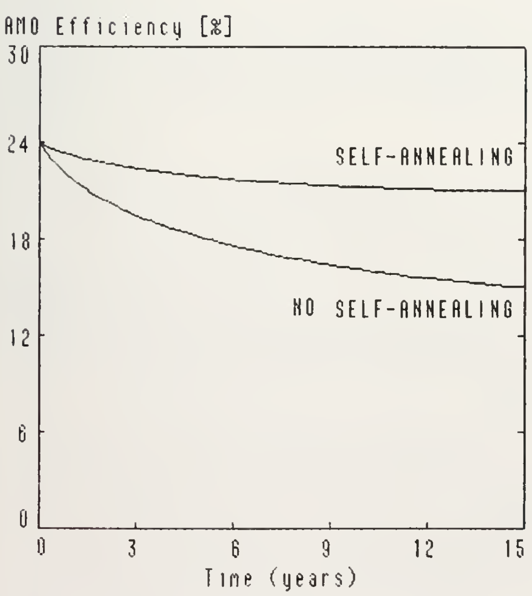

Fig. 3. Efficiency of the silicon concentrator solar cell vs. lifetime in GEO (theory).

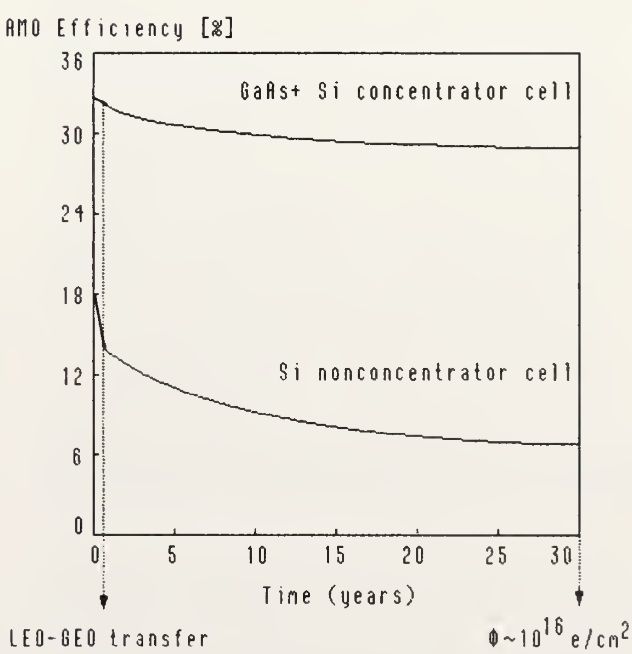

Fig. 4. Efficiency of the Si+GaAs tandem concentrator solar cell vs. lifetime in GEO (theory).

B3.4 Prospects of application of solar arrays with concentrators on near-Earth orbits

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A.S. KOROTEEV

ABSTRACT

The paper lists the results of research and development of solar arrays with solar radiation concentrators.

It is shown that solar concentrators reduce the amount of the semiconductor material, photovoltaic converters are made of, and substantially lower the space radiation effect on photovoltaic converters with resulting service life increase.

RESUME

Cet article présente les résultats de recherche et développement des panneaux solaires équipés de concentrateurs.

On démontre que l'utilisation de concentrateurs permet de réduire la quantité de matériau semi-conducteur qui compose les cellules solaires, et diminue considérablement l'effet des irradiations cosmiques sur les cellules photovoltaïques, ce qui a pour effet d'augmenter leur durée d'utilisation.

It is known that solar arrays with silicon photovoltaic converters are widely used for low power supply (from hundreds to thousands of watts) on spacecrafts with the active operation time from some months to 2-3 years.

Solar arrays are inexpensive and have sufficient specific power (20-40 W/kg). The solar energy-to-electricity conversion efficiency of silicon solar arrays is approximately 14 %. Yet, solar arrays are not free from limitations which impede their use in solving a number of space application problems. To begin with, this is the deterioration of characteristics under the influence of space environment. With multiple passing the Earth radiation belts the rate of photovoltaic converters degradation can amount to 40 % a year.

The problem of achieving durable service life of solar arrays with the end-of-life specific power no less than 70 W/m^2 is primarily related to the slowing-down of photovoltaic converters performance deterioration.

To provide the solution of the abovementioned problems investigations of new radiation- resistant materials, possible photovoltaic converters doping with lithium and development of selective protective coatings,etc. are being carried out.

The present techniques of solar array protection permit only a slight reduction of the degradation because they do not sufficiently prevent the influence of space environment factors and on-board atmosphere on photovoltaic converters. Besides, the prospective radiation-resistant photovoltaic converters are much more expensive - they cost tens times more than those which are used at present.

The indicated problems can be solved using solar arrays of radically new designs. Such arrays employ solar energy concentrators protecting photovoltaic converters from the effects of space environmental factors.

The schematic of one version of a photovoltaic converter with a solar energy concentrator is shown in Fig. 1.

Concentrators can be manufactured of carbon-filled plastic with 0.05-0.1 μm

aluminum or silver mirror coatings. Manufacture of concentrators by galvanoplastics is considered as an attractive method.

Highly efficient, radiation-resistant GaAs-based concentrators have been developed which are designed for concentrated solar radiation flux (C=80...100--fold), 20 % efficiency and an operating temperature up to 150 °C.

The investigations conducted at the Scientific-Research Institute of Thermal Processes (NIITP) have substantiated the solar concentrator scheme selection. They demonstrated that the orientation accuracy of the one-mirror scheme not more than ±1.5 angle degrees was sufficient. It is also shown that the accuracy of concentrator manufacture should not exceed 12th accuracy rating and the permissible angle of the surface irregularities misalignment is 3-5 milliradian. These requirements are quite reasonable, they allow selection of the technological equipment and concentrators cost reduction.

As noted above, using concentrators cuts down the expenditure of costly semiconductor materials (GaAs) which enables annealing of radiation-induced imperfections at elevated (475K) temperature. The mass and cost of solar arrays with concentrators are expected to be less as compared to conventional (planar) arrays. Apart from annealing of radiation-induced imperfections GaAs semiconductors provide more intensive photoelectric current and higher temperature stability.

The main element of the solar array design with concentrators is a unified rectangular cell which measures 36mm x 45mm. The cell design employs a one-mirror off-axis optical reflector system which was developed at NIITP. The cell makes advantage of newly-made GaAs photovoltaic converters.

Main Technical Characteristics of the Cell

Electric power	0.37 W
Photovoltaic converter efficiency	17 %
Optical efficiency	85 %
Specific electric power	200 W/m², 40 W/kg
Permissible angle of divergence at Sun orientation	±1.5°
Lifetime (at 15 % degradation-minimum level of initial power reduction- on radiation hazardous orbits)	7 years

Based on unified cells, it is possible to develop solar arrays of different power levels and configurations.

New principles of solar battery construction have called for new approaches towards the ground optimization program aimed at the verification of high reliability and durable service life. To the present day experimental investigations have been carried out on optical and photovoltaic characteristics of separate modules consisting of 9 cells and solar array panels (500mm x 600mm). Dynamic tests of panels were conducted as well as strength and acoustic testing.

In Fig 2 the module dimensionless power $\bar{N}$ is plotted as a function of the Sun misorientation angle.

Ground tests showed that photovoltaic converters are well protected from cosmic rays by the concentrator structure, thus providing the service life of solar arrays with concentrators on radiation hazardous orbits of 4,000-12,000 km altitude up to 5-7 years, the density of protection therewith being 0.5-0.75 g/cm².

Fig. 3 presents specific power N of solar arrays with concentrators and planar solar arrays as a function of the flight altitude H at the end of 5 years service life. The advantages of solar arrays with concentrators are obvious.

To solve the problem of increasing the power systems service life and photovoltaic conversion efficiency and to assure also solar arrays cost reduction, NIITP in cooperation with the Scientific-Production Union "Yuzhnoye" has been preparing a space experiment on solar energy concentrators on board the spacecraft AUOS (Automatic Universal Orbital Station) assigned for 1992 and further.

It is anticipated that power-generating characteristics of solar concentrators with photovoltaic converters of various designs will be studied and also quantitative data on the decrease of these characteristics deterioration will be obtained.

In accordance with REGATTA international program the Institute of Space Research is developing a commercial spacecraft-platform (named Small Space Laboratory) for investigations of near space, near-Sun and interplanetary space and stars. The spacecraft is constantly and precisely Sun-oriented (±4"), the operation time is 5...7 years. The photovoltaic array with solar energy concentrators ($N_{(e)}$ 250 W) developed at NIITP was chosen as an alternative power supply system for this spacecraft.

The schematics of the location of solar arrays with concentrators on the spacecrafts AUOS and "Small Space Laboratory" are shown in Fig. 4, 5.

The Scientific-Research Institute of Thermal Processes invites concerned companies to cooperate in research and optimization of the technology of highly-efficient space solar arrays with concentrators and in research and manufacture of demonstrator prototypes.

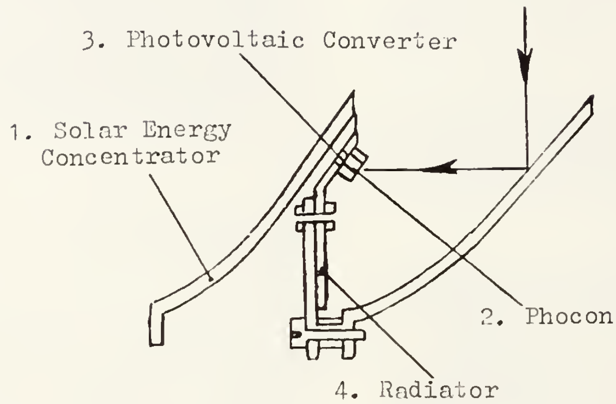
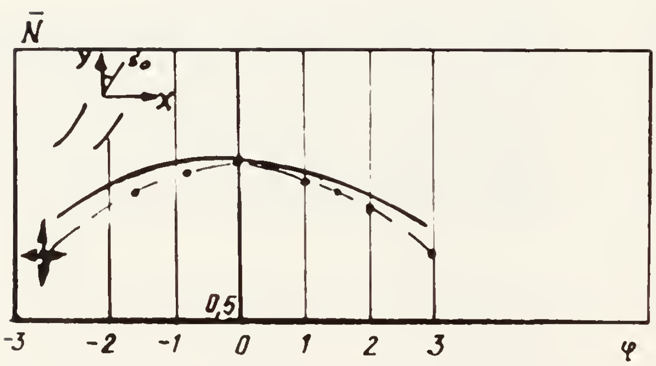


Fig. 1. Schematic of Photovoltaic Converter with Solar Energy Concentrator.



- analysis
--- experiment

Fig. 2. Module Dimensionless Power as a Function of the Sun Orientation Divergence Angle.

- with solar concentrators
▪ with protective coating
--- without protective coating

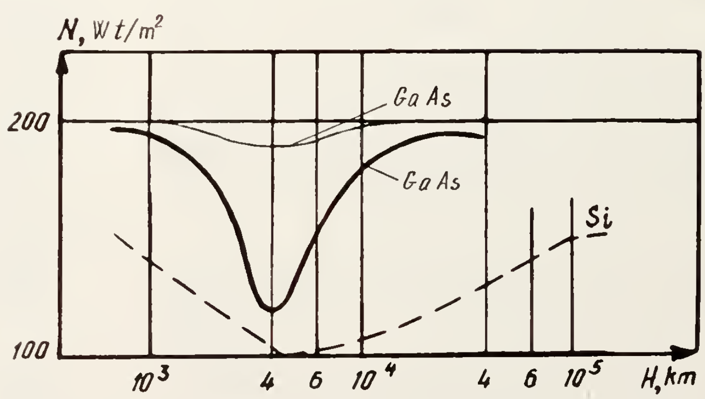


Fig. 3. Specific Power of Solar Arrays with Concentrators and Planar Solar Arrays as a Function of the Flight Altitude at the End of 5 Years Service Life.

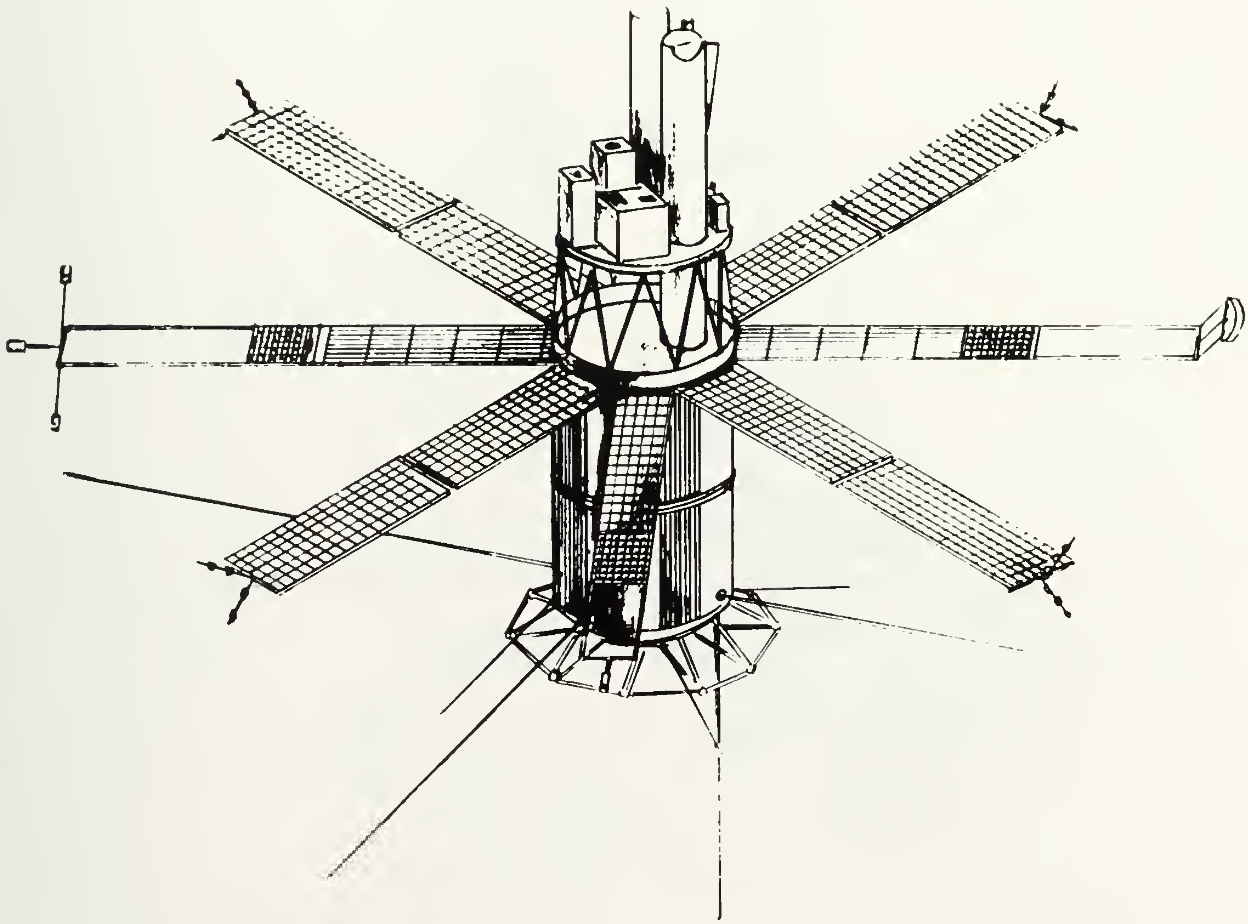


Fig. 4. Schematic of the Location of Solar Arrays with Concentrators on Board the Spacecraft AUOS.

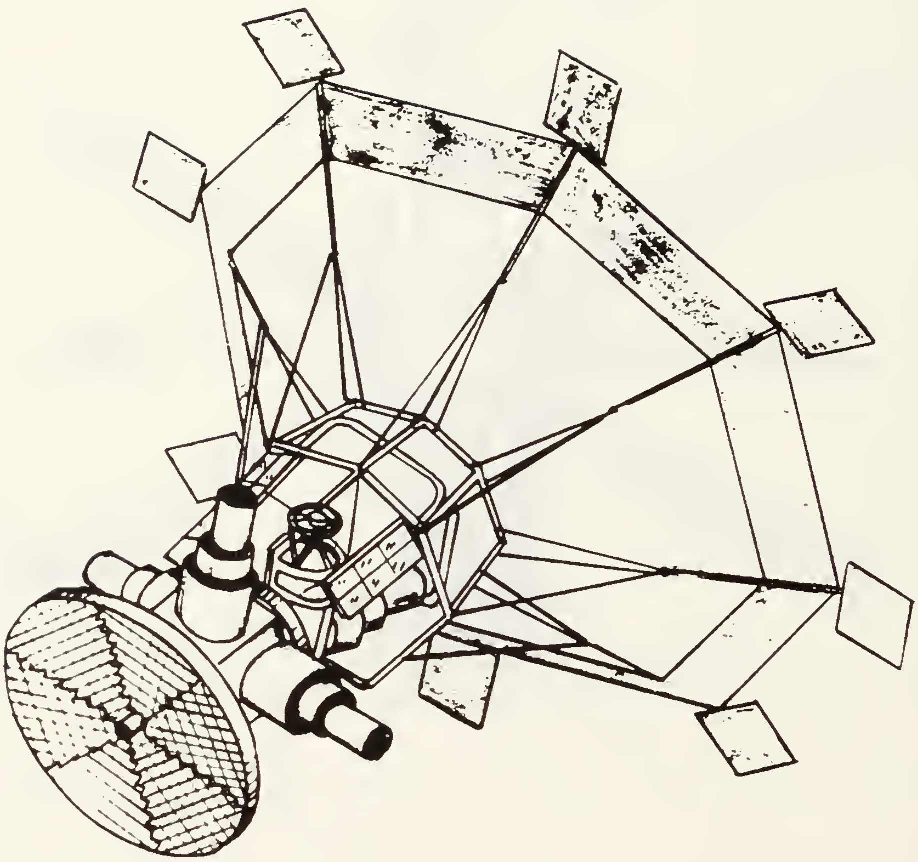


Fig. 5. Schematic of the Location of Solar Arrays with Concentrators on Board the Spacecraft "Small Space Laboratory".

SPS 91

B3.5 Solar photovoltaic efficiency of structures on the ternary II-VI compounds

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We have considered a present state of the multi-layer Solar Cell development : physical simulation of characteristics, principles for the graded band gap layer formation to achieve correlation between the solar cell spectral characteristics and the solar spectrum, for example :

CdS/CdTe(CdMnTe, CdZnTe)/ZnTe, ZnSe(CdS)/$CuInSe_2$ etc.

systems which have low resistivity Ohmic contacts to the layers to increase the I-V characteristic filling factor up to 75 % and the open-circuit potential as well as other factors that limit solar cell photovoltaic efficiency to about 17 % and result in photon degradation.

B4.1 Different space electrochemical conversion and storage systems

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SUMMARY

In most cases, electric power source of spacecrafts comprise storage and energy conversion devices which operate by electrochemical way. In this paper, the main primary and secondary electrochemical couples used are described in terms of principle characteristics, state of the art and improvements which are expected in the near future. In a second part of this paper is discussed the adaptability of these solutions to the different space missions and the desirable axis of investigation in order to fulfill future needs as energy production in space.

RESUME

La plupart des systèmes spatiaux comportent dans leur système d'alimentation électrique des dispositifs de stockage et de conversion d'énergie par voie électrochimique. Dans cet article sont décrits les principaux couples électrochimiques utilisés primaires et secondaires (ces derniers étant couplés avec un générateur photovoltaïque ou une machine thermique), leurs principes, leurs propriétés, l'état de l'art et les améliorations attendues dans un proche avenir. La seconde partie de l'exposé est consacrée à l'adéquation de ces filières aux différentes missions spatiales et les axes d'investigations souhaitables pour faire face à des besoins futurs comme la production d'énergie dans l'espace.

I. General remarks

Electric Power sources used in spacecrafts comprise a great number of energy storage and conversion devices by electrochemical way, with however an initial selection criteria of couples which is an energy density as much attractive as possible. In most cases, the used devices have not been especially developped for space utilisation but for ground applications (traction, portable equipements...), these systems have been adapted to our applications in order to fullfill the following requirements :

- ability of working in space environment, (vacuum zero gravity)

- good reliability,

- good energy density,

- lifetime in the case of satellite and space station applications.

These electrochimecal devices comprise two groups which are :

- primary systems which allow only one discharge,

- secondary systems, or accumulators, which can under go a certain number of charge-discharges cycles, according to the nature of the couple.

These devices are systematically used in a all kinds of spacecrafts independantly of the nature of the payload, in the case of applications mentioned in this session (energy production in space and redistribution) a preselection of devices can be done and will be discussed at the end of this paper.

II - Different electrochimecal systems used in a space applications

2.1. SECONDARY DEVICES

2.1.1. Nickel-Cadmium accumulators

2.1.1.1. Properties of the couple

Electrode + : Ni $(0H)_2$
Electrode - : Cd $(0H)_2$
Electrolyte : KoH solution 6N immobilized in a separator made of tissue.

Reaction at the level of the electrodes

$$2\ Ni\ OOH + Cd + 2\ H_2O \underset{charge}{\overset{discharge}{\rightleftharpoons}} 2\ Ni(OH)_2 + Cd(OH)_2$$

Mean voltage : 1,3 V

Adaptation of this device for space applications needed :

- the development of a leak proof element,

- a resizing of the negative electrode in term of capacity, in order to obtain a efficient recombination of oxygen which is produced during overcharge.

2.1.1.3. State of the art

Technology :

- Active oxydes are located in porous structures made of sintered nickel.

- Impregnation of the porous structures by active oxides is obtained by chemical or electrochemical way.

- The separator is made of polyamide tissue.

Packaging :

- Cylindric accumulators, when a few cycles are required (application in launchers).

- Prismatic accumulators.

This design is adapted when big capacities and a great number of cycles is required, it allows a better heat dissipation and a higher compacity at the level of a battery mounted in a satellite.

Performances :

Energy density :

From 35 Wh/kg to 42 Wh/kg in accordance with the capacity of the element.

Lifetime :

In the case of low earth orbit operation.

Dept of discharge	Temperature	Lifetime
40 %	25° C	4 years
15 %	5° C	10 years (estimated)

2.1.2. Nickel hydrogen accumulator

2.1.2.1. Properties of the couple

Electrode + : Ni $(0H)_2$

Electrode - : Porous electrode with platinized carbon

Electrolyte : KoH solution 6N immobilized in a separator made of tissue.

Reaction of the level of the electrodes.

$$Ni\ OOH + 1/2\ H_2 \underset{discharge}{\overset{charge}{\rightleftharpoons}} Ni(OH)_2$$

mean voltage : 1.35 V

2.1.2.2. State of the art

Technology :

- Positive electrode : same technology as for Ni Cd accumulator.

- Negative électrode : platinized carbon mixed with a binder as PTFE, sintered or laminated on a metallic support as grid or foam. (Same technology of electrode as for fuel cells).

- Separator : polyamide tissue

- Electrode stack mounted in an hydrogen high pressure vessel (up to 70 bars at the end of charge).

- Performances

Energy density :

From 50 Wh/kg to 55 Wh/kg

Lifetime (expected) :

1000 cycles in geostationnary orbit operation conditions with :

70 % depth of discharge,
0° C to 20° C temperature.

2.1.3. Silver Cadmium accumulators

Properties of the couple and performances

Electrode + : Aq_2O_2
Electrode - : Cd $(OH)_2$
Electrolyte : KoH solution 7N
Porous separator : Cellophane

Reactions of the level of the electrodes :

$$Aq_2O_2 + Cd + H_2O \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} A_{q2}O + Cd(OH)_2 \text{ Mean voltage : 1,38 V}$$

$$Aq_2O + Cd + H_2O \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} 2Ag + Cd(OH)_2 \text{ Mean voltage : 1,16 V}$$

Energy density : from 40 Wh/kg to 70 Wh/kg

This type of accumulator was mainly used in the frame of the first satellite program, due to the requirement of lifetime for the satellites of today its cyclability is not sufficient, this solution is in way of beeing abandonned (exepted for some specific missions).

2.2. PRIMARY DEVICES

2.2.1. Silver zinc cells

2.2.1.1. Properties of the couple

Electrode + : Ag_2O_2
Electrode - : $Zn(OH)_2$
Electrolyte : KoH solution 7N
Porous separator

Reaction at the level of the electrode

$$Ag_2O_2 + Zn + H_2O \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} Aq_2O + Zn(OH)_2 \quad V = 2{,}0 \text{ V}$$

$$Aq_2O + Zn + H_2O \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} 2Ag + Zn(OH)_2 \quad V = 1{,}6 \text{ V}$$

In the frame of primary couple utilization, cells a filled with electrolyte just before using. This couple can also be used as a secondary couple, but due to its relatively low cyclability it is not used in space applications.

2.2.1.2. State of the art

Technology :

Electrode + : Sintered powder on a silver grid with a binding agent (PTFE).

Electrode - : Sintered powder with a binding agent (PTFE) and with a small fraction of HgO.

Porous separator : Cellophane.

Energy density ≈ 200 Wh/kg

Packaging : Prismatic container made of plastic equiped with a safety valve.

2.2.2. Lithium cells

2.2.2.1. Lithium-thionyl chloride cells

2.2.2.1.1. Properties of the couple

Electrode - : Li
Electrode + : Porous carbon
Electrolyte : Li $SOcl_2$ + Li Al Cl_4 1,8 M with a porous separator

Reaction at the level of the electrodes

$4Li + 2\ SOcl_2 \dashrightarrow 4liCl + SO_2 + S$

Open circuit voltage : 3,65 V

2.2.2.1.2. State of the art

Technology :

- Electrode - : lithium foil colaminated with a metallic grid

- Electrode + : porous carbon deposition on a metallic grid with a binder (PTFE).

- Separator : glass fiber tissue.

Performances :

Energy density : 300 Wh/kg to 400 Wh/kg according to the versions.

Packaging

- D size C size and A size

- Cylindrical with a variable size according to the desired capacity.

2.2.2.2. Lithium-sulfur dioxyde cells

2.2.2.2.1. Properties of the couple

Electrode - : Li
Electrode + : porous carbon
Electrolyte : acetonitrile + propylene carbonate + SO_2 + LiB + porous separator.

Reaction at the level of the electrodes.

$2Li + 2SO_2 \dashrightarrow Li_2\ S_2\ O_4$

Voltage : 3 V

2.2.2.2.2. State of the art

Technology :

Electrode - : lithium foil colaminated with a metallic grid.

Electrode + : porous carbon desposition with PTFE as binder on a metallic grid.

Separator : glass fiber tissue.

Packaging :

D size and C size.

2.2.2.3. Fuel cells H2-02

2.2.2.3.1. Properties of the couple and principle.

In this type of cell, free enthalpy variation induced by synthesis of the water is converted in electric energy (240 kj per mole of water) and which provides an open circuit voltage of 1,18 V per electrochemical cell.

Constitution of the electrochemical cell is the following :

Electrode + : porous electrode containing catalysts, in contact with electrolyte and 0_2.

Electrode - : porous electrode containing catalysts, in contact with H_2 and electrolyte.

Electrolyte : acid or basic aqueous solution.

In the case of cells working with basic electrolyte (KoH solution), reactions at the level of the electrodes are the following :

$$\text{Electrode+}\quad 1/2O_2 + H_2O \longrightarrow 2OH^- \ \_2e$$

$$\text{Electrode-}\quad 2O\ H^- + H_2 \longrightarrow 2H_2O + 2e$$

$$\overline{\qquad 1/2O_2 + H_2 \longrightarrow H_2O \qquad}$$

In order to work in space conditions (mainly zero gravity and sometime strong acceleration conditions) adaptation of this system needed development of devices using immobilized electrolyte.

2.2.2.3.2. State of the art

(Case of cells working at low temperature, about 100° C)

. Technology at the level of the stack. (association of electrochemical cells)

- Electrodes : platinized porous structures, hydrophobic or hydrophilic, deposited are a nickel grid.

- Electrolyte : KoH solution of about 8N, immobilized in a hydrophobic porous matrix (asbesto, zircone...).

- Heat dissipation obtained by a circulation of fluid inside of the cells.

- Water elimination obtained under vapour phase by hydrogen flux along the negative electrode.

. Reactive gas storage.

- gas under pressure,

- gas stored in super critical state.

Utilisation of one of the two solutions is function of the required autonomy.

. Performances

Energy density is the most attractive when long duration missions are required, the order of magnitude is about 1000 Wh/kg for a power delivery from 2 kW to 6 kW during 2 weeks.

III - Investigations in Progress

3.1. MAIN GOALS

If we take into account the facts that energy need are always increasing due to the space missions which are more and more complex and the cost of the embarked kilogram which is still very high, one of the most important goals in the frame of research and development actions is the improvment of the energy density. This action induces :

- application of new technologies in order to increase performances of existing devices,

- spatialization of new electrochemical couples.

If we exept reliability and security requirements that new systems must fullfill, according to the missions these ones must present :

- a same lifetime as existing devices,

- long storage periods without alteration of the performances before activations (case of a planetary mission).

3.2. SECONDARY SYSTEMS

3.2.1. Nickel cadmium accumulators

New technologies used successfully in portable equipments look promising at the level of mass saving, it concerns new supports for active hydroxydes made of nickel foams which are impregnated by mechanical way. First estimations permit to hope an energy density of about 55 Wh/kg at the level of the final device. Feasability studies are in progress.

3.2.2. Nickel hydrogen accumulators

Adaptation of the same technology than in 3.2.1. at the level of the nickel electrode should permit to obtain a density energy increase of about 20 %. Another way of investigation which should look promising is the adaptation of hybride as mean of hydrogen storage instead of a pressure vessel. This solution should not bring a real increase of energy density but should allow construction of more compact accumulators with a simple battery design.

3.2.3. Sodium sulfur accumulators

3.2.3.1. Principle and properties of the couple

Electrode - : molten sodium,
Electrode + : molten sulfur mixed with a conductive element (graphite),
Electrolyte : Na^+ conductive ceramic (β Alumina).
Working temperature : from 300° C to 400° C.

Reaction at the level of the electrodes.

$$2\,Na + xS \underset{charge}{\overset{discharge}{\rightleftarrows}} Na_2S_x$$

Voltage :

1,7 volts < V < 2 volts

3.2.3.2. State of the art and necessary adaptations for space applications

Energy density :

From 70 Wh/kg to 230 Wh/kg according to the capacity of the element. (In the case of cells which are between 50 Ah and 100 Ah we obtain an energy density of about 170 Wh/kg).

Necessary adaptations :

- Immobilization of sodium and sulfur with wicks in order to permit the cells to work in zero gravity.

- Inprovement of reliability and reproducibility in term of lifetime.

- Development of a battery device.

Works in this axis are actually in progress in the United States.

3.2.4. Lithium accumulators (ambiant temperature couples)

3.2.4.1. Principle and properties of the choosen couples

Electrode - : pure lithium
Electrode + : intercalation components as T_iS_2 and V_20_5
Electrolyte : organic solvents mixture as dioxalone, THF with a salt like $LiClO_4$ or $LiAsF_6$.
Presence of a porous polymer separator between the electrodes.

Mean voltage :
V = 2,1 volts for Li/TiS_2 couple
V = 2,5 volts for Li/V_20_5 couple.

3.2.4.2. State of the art

- Energy density = 100 Wh/kg
- Cyclability : about 300 cycles with Li/TiS_2 and 100 cycles with Li/V_20_5.
- Packaging : A.C. and D. size.

3.2.4.3. Necessary adaptation

These couples very promising in term of energy density need two type of adaptations wich are :

- improvement of the cyclability,
- realization of prismatic high capacity cells.

3.2.5. Secondary full cell system

3.2.5.1. Principle

This system can replace a conventional battery with accumulator mainly when high powers are required. This system contains :

- a fuel cell stack
- a water electrolyser,
- 0_2 and H_2 tanks (pressure vessels),
- a water tank.

In the frame of space applications, immobilized electrolyte in porous matrix are used in the full cell stack as in the electrolyser. Electrolysis of water is obtained by injecting water vapour in one of the gas loop.

3.2.5.2. State of the art and performances

Studies are still in progress in the USA and in Europe for future applications in Space-Stations. Concerning performances, we can expect to obtain an energy density of about 200 Wh/kg when a mean power of 100 kW is required in the frame of a low orbit application.

IV - Field of application of the different systems with all types of payloads.

Type of spacecraft	Operational devices	Future or improved devices
Launchers (primary)	Ag-Zn primary Ni Cd	Li battery
Planetary probes	Li batteries	
GEO satellites	Ni Cd Ni H_2	NiH_2 Li batteries (secondary)
LEO satellites	Ni Cd	Ni H_2 Ni Cd Na S
Space stations	Ni H_2	Ni H_2 secondary fuel cells
Space shuttles	Fuel Cells	Fuel cells

V - Electrochemical storage systems which can fulfill the required conditions in the application solar electric energy production from space

In this type of application two cases can be considered :

- Energy producted from a spacecraft operating in geostationary orbit.

- Energy produced from a spacecraft operating in geosynchronous orbit.

In the case of the application in geostationary orbit, two facts must be taken in consideration :

- The spacecraft can send energy continuously to a terrestrial station.

- Eclipse duration (and only 90 times per year) is relatively low in comparition with the time of the orbit.

Due to these conditions, energy storage devices operate under :

- a relatively few cycles,
- a low rate of charge and discharge,

in this application. These devices should fullfil the same requirements as for other satellites and space stations, with a particular mention for lithium secondary cells and secondary fuel cell systems which look promising for the future in term of very attractive mass budgets.

Concerning the applications in geosynchronous orbit conditions, in spite of solar collectors which can work continuously, we can consider that energy emission duration to a terrestrial station in relatively low. In this case of application, energy storage devices must present a good compromise between energy density and power density, and new developments are necessary. In order to increase the power density, several solution can be suggested as :

- thin electrodes technology, which allow a bigger surface of electrode in a same volume,

- electric charge collection by bipolar systems,

- efficient heat dissipation systems.

In the frame of high power density applications, some works look successfully in progress, so is the case of :

- Ni Cd cells developped under military contract, with SONAR power source as application,

- Pb cells with bipolar electrodes developped in the USA for pulsed LASER power source as application.

B4.2 High power conditioning for space applications

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ABSTRACT

This paper is specially devoted to the description of high power conditioning for space applications. High power conditioning means the platform power supply concept which interfaces the energy sources (solar array and battery) with the users and the payload electrical distribution which describes the interfaces with the platform and the power supply concept of the payload. The state of the art topologies are based on regulated bus voltage concepts involving conductance control regulators.

RESUME.

Cet article décrit le conditionnement de puissance pour des applications spatiales. Le conditionnement de puissance signifie concept d'alimentation électrique de la plateforme qui interface les sources d'énergie (panneaux solaires et batteries) avec les utilisateurs ainsi que la distribution électrique de la charge utile qui concerne les interfaces avec la plateforme et les concepts d'alimentation des équipements de cette charge utile. L'état de l'art de ces topologies est bâtit autour d'un concept à bus régulés en tension avec des régulateurs à contrôle en courant.

1. INTRODUCTION

Spacecraft power systems are responsible for the efficient transformation of the available energy (solar, chemical, nuclear) into electrical power, properly distributed to other systems (thermal, attitude control, housekeeping etc.) and payloads. For earth orbiting satellites, the power system is composed of solar arrays as the primary energy sources, batteries for the provision of energy storage in eclipse periods, the power conditioning and the harness for the energy transformation and distribution.
Spacecraft Power Systems were for a long time considered as of secondary importance and considered to be relatively conventional and hence the power system rarely received essential effort necessary for its optimisation. So much so that the Power System mass figures referenced to the total mass of the dry satellite (without fuel) for geosynchronous and low orbit spacecrafts were generally around the figures listed in the following table, which excludes the converters masses contained inside the user equipment.

	Geo synchronous S/C	Low orbit S/C
Power system	0.33	0.26
Solar array	0.09	0.08
Batteries	0.12	0.08
Power conditioning	0.08	0.04
Harness	0.04	0.06

If such ratios were acceptable for satellites dealing with payloads requiring a few kilowatts, they become prohibitive for large spacecrafts or space stations.

The power system is one the driving concepts of the space station design. As it includes the largest element (solar blanket) and the heaviest component (batteries) of all subsystems it directly interacts with the requirements of the other subsystems (Dynamic problems for the structure, drag and stabilisation for the attitude control, electrical conversion efficiency for the thermal management subsystem are typical critical areas which require now major attention).
The power conditioning associated with spacecraft power systems has been the "heart and mind" of the system itself, as to an increased extent, the power electronics has taken over the power management function (power flow control, balanced energy management of multiple power sources and storage elements, autonomy of operation of the system during all mission phases, elimination of potential mission critical failure modes) whilst maintaining the basic objectives of high electrical efficiency and low mass.
Associated with the increased sophistication of the power system is the increasing interdependence of major spacecraft subsystems and payloads. Every power system choice (power bus topology, voltage levels, AC or DC etc) has to be carefully assessed with respect to all the other system interfaces, both physical and performance targets.
This paper attempts to describe the state of the art topologies for the power conditioning of a spacecraft for major applications that are the geostationary and the low earth orbit missions. While they aim to achieve the same system objectives, the power conditioning for a platform and a payload call to different topologies which will be described separately.

These topologies which have been finalised after intensive trade-offs as a result of several study contracts present the common feature to be architectured around a regulated bus voltage concept, the voltage being different depending upon the application (space station, geostationary or low orbit missions).
The optimisation of the power conditioning concepts as far as mass and efficiency are concerned brings a consistent contribution to the best use of Power from Space as being the untwistable way of the energy between the power sources and the users.

2. THE SPACECRAFT POWER SYSTEM

2.1 Main objectives

The unique feature of the majority of spacecraft power system design is the requirement to provide continuous power to the spacecraft payloads and service subsystems (e.g. attitude control, telemetry and telecommand, thermal etc.) in an environment where the power source is routinely interrupted by the eclipse of the source (usually a solar array), resulting from the passage of the satellite through the Earth's shadow.
Other mission features, such as the degradation of the solar array's performance as a result of radiation induced damage, tilting of the array with respect to the sun and widely fluctuating load consumption, are drivers in the definition of the 'ideal' power system design concept.
Last but not least, reliability is an essential parameter in the choice of a power system for a spacecraft which may be required to operate autonomously for up to a decade. Similarly, the system must be able to cope with failures in payload and non essential equipment and safely recover normal operation, with the minimum disturbance to unaffected spacecraft loads.
A spacecraft power system, therefore, comprises the following basic functions:

- **Energy source**: usually a solar array, sometimes a radio-isotope generator (RTG);
- **Energy storage**: mainly nickel/cadmium or nickel/hydrogen batteries, used to provide power in eclipse or peak power in sunlight;
- **Power-control unit**: power electronics required to manage and regulate the system;
- **Power distribution and protection**: switchgear and protection devices;
- **Secondary power conversion**: converters and inverters associated with subsystems and payloads.

The key problem to be solved in power-system design is associated with the charge and discharge of the batteries and, as can be easily understood, the spacecraft orbit has a major role in determining how significant a task this is.

Orbit are chiefly grouped in four main categories:
- **LEO** - low earth orbit - near the earth, with an eclipse of about half an hour for a 1.5 hour orbit;
- **GEO** - geostationary orbit fixed 36 000 km above the earth, with an eclipse of 1.2 hour for a 24 hour orbit during two periods each year;
- **HEO** - Highly elliptical orbit - perigee near earth, apogee far away - variable eclipse/orbits;
- **Deep Space** - few eclipses, but big variation in solar energy.

Of the above, LEO is unique in its high eclipse-to-sunlight ratio (about 30%), all the others having a relatively low eclipse operation, relative to the orbit period. The impact for a LEO power system is then unique, in that a 1/2hour heavy discharge must be replenished in a period of less than one hour. These inherent high charge rate and associated high power requirement imply that a very careful design approach is desirable, since the batteries in such an orbit are usually essential to the mission success and the method of charge significantly affects the size of the required solar array.
The other orbits, whilst less stressing, have varying degrees of difficulty, dependent on the eclipse operational requirement (e.g. reduced or full eclipse power) and the power level and reliability requirements imposed by the mission.
Again, the various missions can be loosely grouped into the following five basic categories.

Science
Any orbit and power level between 200 W and 1.5 kW; scientific requirements can have major impact on power system choice, e.g. payloads with extremely low electric, magnetic and electromagnetic fields can result in the rejection of conventional regulation schemes (Pulse Width Modulation), materials and components (e.g. nickel-cadmium batteries and relays).

Telecommunications
Geostationary orbit; full telecommunications in eclipse at power levels up to 3 kW or direct television broadcast with low eclipse power (ca. 500 W), but high sunlight power of up to 10 kW and sometimes a combination of both. In addition, telecommunication spacecrafts have to be designed to provide a high adaptability to new payloads and eclipse requirements and achieve a high reliability, autonomy in-orbit and last, but not least, low cost!

Earth Resources
Low earth orbits; high power (circa 6 kW) with high peak power requirements of up to 10 kW; high stress on batteries, which are key elements in determining mission lifetime.

Meteorology
Geostationary orbit at power levels between 300 W and 1.5 kW.

Manned Missions
LEO space station or laboratory applications or manned vehicles with power levels in the range 3 to 30 kW. These missions in addition pose severe reliability, safety and maintenance requirements, which are unique.

2.2 General concept

The power conditioning, part of the spacecraft power system consists of all equipment which controls and distributes the power from the energy sources to the users. Its central position in the power system is highlighted in fig. 1 which details the general block diagram of such a system.
The level of the distributed voltage is of prime importance in the overall power system performances. Several standards have been developed varying with the level of regulation of the delivered voltage. The selection of the most adequate concepts have been the result of an in-depth system trade-off involving mass, efficiency component availability, safety and plasma interactions as major drivers.

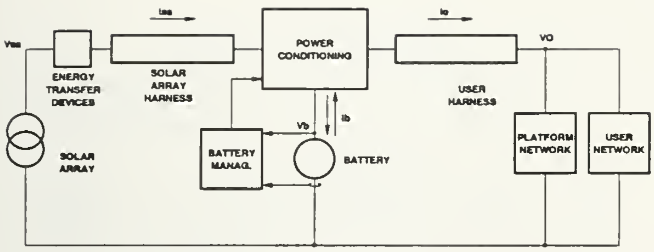


Fig. 1: General power system configuration

For the last thirty years, more than 5000 spacecrafts have been launched and operated in low, elliptic or geostationary orbits around the earth. Whatever the type of satellite, civil or military, scientific or application and the type of orbit, the block diagram of the spacecraft's electrical architecture identifies two complex systems, the platform and the payload interconnected by a distribution box unit (DBU) as shown in fig. 2.

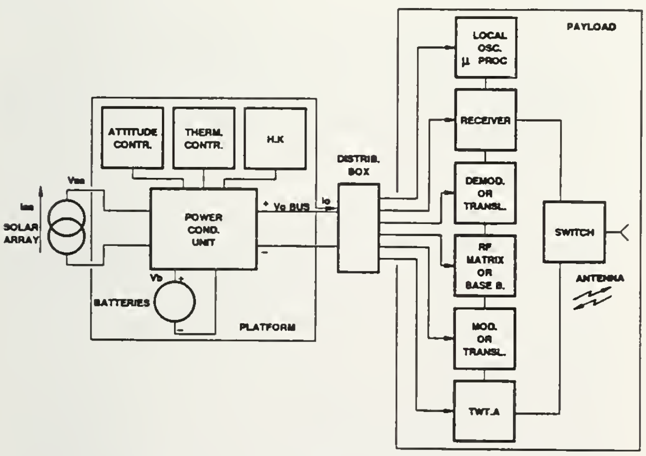


Fig. 2: General block diagram of the electrical architecture of a telecommunication satellite

The platform is responsible for the servicing of the spacecraft in orbit (attitude control, thermal, housekeeping, data handling) as well as the energy supply of the complete satellite. Two energy sources are available, the primary source composed of solar cells, and the energy storage source, generally Ni-Cd or Ni-H_2 batteries, for eclipse operations or peak power demands. The power conditioning converts the requested energy into an electrical form (V_o), distributed to the user network through one or several bus bars and guarantees the reliable working of the system. According to the selected power system topology, the voltages of the solar array (V_{sa}), the battery (V_b) or the bus bars (V_o) are independent, a regulated voltage V_o being distributed to the users. The payload is responsible for the correct operation of the payload internal conversion and distribution network. This latter is composed of several functions which are supplied under a centralized or decentralized form via DC/DC or DC/AC converters connected to the DBU.

3. THE PLATFORM POWER SUPPLY

While the platform power conditioning presents the principal feature to deliver a regulated voltage to all users whatever the spacecraft mission and orbit are, the concepts are appreciably different for a geostationary and a low earth orbit mission. And in this latter application the same applies between an automatic and a manned mission.

3.1 <u>The geostationary orbit concept</u>

The regulated bus topology constitutes the logical step in the evolution of a geosynchronous power system optimisation, as it definitively decouples the necessary but very different energy sources (solar array and energy storage batteries) from the electrical network of the spacecraft.
A typical configuration of this topology is represented on figure 3.

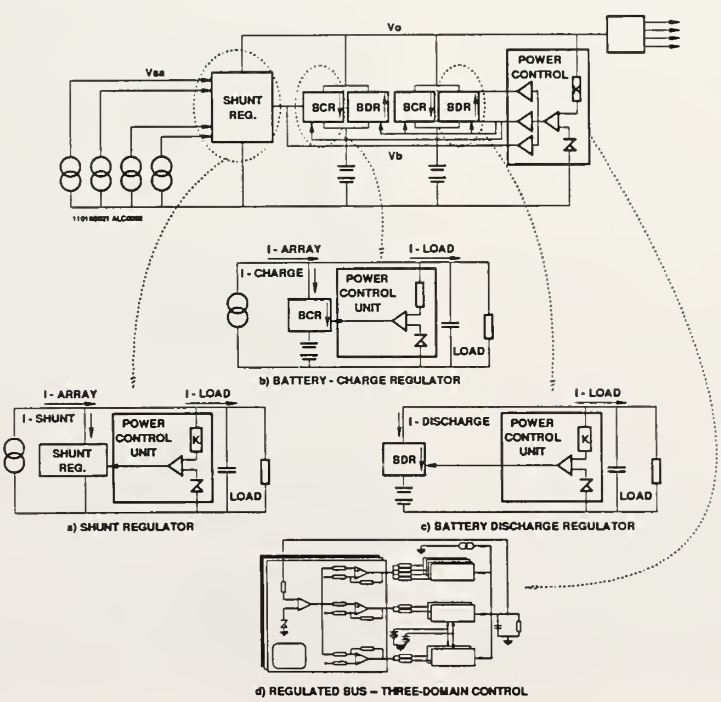


Fig.3: Regulated bus concept for the geostationary orbit applications

The power conditioning concept involves three different non dissipative voltage regulators:

- the shunt regulator interfacing the solar array energy source and the users (figure 3a);
- the battery charger (BCR) which regulates the bus voltage V_o by charging the battery with a variable charge current i_{BC} when the shunt regulator is not operating. This charge current cannot overpass a preset value i_{BCM} imposed by the battery management system which automatically activates the shunt regulator and charges each battery with this constant current value (figure 3b);
- the battery discharger (BDR) which interfaces the batteries and the user network by regulating the bus voltage V_o with variable battery discharge current i_{BD} (figure 3c).

These regulators operate in a sequential mode activated by a common control signal generated by the Power Control Unit (PCU) which constitutes the heart of the power conditioning feedback system of the platform power system. Such a sequential operation is called three domain control (figure 3d), as it will be described next.

3.1.1 The regulated bus principle

An imposed constant voltage V_o is distributed during both sunlight and eclipse periods by means of active control systems (Direct Energy Transfer 3 Domain Control), making the energy sources individually isolated. As a consequence, the excursion range of the bus voltage is drastically reduced, the locus of the system operating points being defined by (figure 4):

$$V_{sa} = V_o \tag{3.1}$$

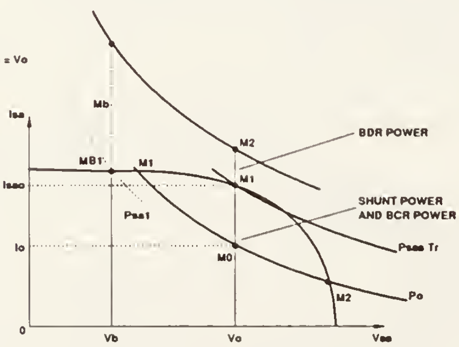


Fig. 4: Solar array operating points with regulated bus power system

As it can be seen from figure 4, the sunlight operating point is defined by the intersection M_1 of the solar array characteristic and the straightline $V_{sa} = V_o$.

The available power P_{sa}, represented by the curve T_{rs}, results in the following characteristics:

$$P_{sa}\,(V_o) = V_o\, i_{sao} = P_o + P_{sh} + P_{ch} \tag{3.2}$$

where P_o is the power required by the loads and P_{sh} and P_{ch} are respectively, the power eliminated by the shunt regulator and that power required for the charge of the battery.

The locus of the system operating points will be the straight line $V_{sa} = V_o$ imposed by the shunt control system. The load power P_o is materialised by the point M_o on this line and the power system is defined by:

$$P_o = V_o\, i_o$$

$$P_{ch} = V_B i_{BCM} = V_o\,(i_{SAO} - i_o) \tag{3.3}$$

$$P_{sh} = P_{SA} - (P_o + P_{ch})$$

where i_o and i_{SAO} are respectively the load and the solar array currents and V_B the time varying battery voltage.

The energy requested by the electrical network in sunlight (platform and payload) and the recharge of the battery is provided by the solar array. The excess energy is radiated to space by means of a non dissipative shunt regulator, in order to maintain the bus voltage at a fixed value. The energy source interface is a non dissipative Battery Charge Regulator (BCR).

A power conditioning unit controls the optimum performance of these regulators. The battery management is generally performed according to a preprogrammed procedure, which will be described separately.

During peak power demands the locus of the system operating points remains the straightline $V_{SA} = V_o$, however the load operating point moves from M_o toward M_1, where the bus voltage regulation is successively, performed by the shunt regulator till $i_{BC} = i_{BCM}$ and by the battery charger regulator alone when:

$$0 \le i_{BC} < i_{BCM} \tag{3.4}$$

During eclipses or during large peak power demands, the locus of the system operating points moves from M_2 toward M_1 exceeding the solar array capability. The battery discharge regulator is activated by the power controller unit, the battery charge and the shunt regulators being deactivated as M_1 is reached. The battery discharge regulator (BDR), a non dissipative control system, regulates the bus voltage to the same value V_o by means of a control signal coming from the PCU with a variable battery discharge current i_{BD}. This concept which is characterised by a complex power conditioning sytem, avoids the oversizing of the solar array by decoupling the energy sources and distributes a constant voltage to the platform and payload equipment. This independent management of the energy sources, even of the same nature, has a further advantage for the design of high power systems, using a multi bus concept, due to the decoupling mechanism existing between sources and buses. Finally, the availability of a quasi reference voltage source V_o, current limited by the power conditioning regulators, is a factor of simplicity and flexibility for the design of the power distribution functions (DBU, EPC and converters) which has to be considered in the overall performance evaluation of power system topologies, including the payloads.

3.1.2 Three domain control

In essence, the regulated bus concept is based on the sequential control of the three major power bus regulators constituting the power conditioning system:

- shunt regulator
- battery charge regulators
- battery discharge regulators

which is achieved by including the 3 regulators inside a signal control loop, as detailed in figure 5.

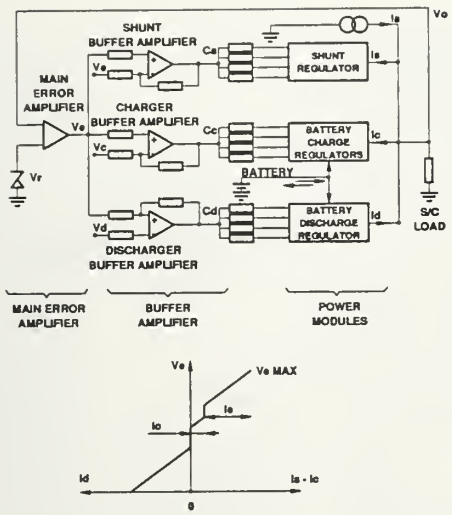


Fig. 5: Regulated bus - 3 domain control

The natural sequence of regulator operation is achieved by the selection of discrete analog domains for each of the three buffer amplifiers, outside of which the amplifiers are saturated in a high or low level. Thus, the control signal (Ve) is located in a domain dictated by the power balance on the bus and regulates the appropriate power module. Due to the gain of the main error amplifier, the resultant bus voltage swing in sequencing the control signal (Ve) from zero to its maximum value is usually less than 1% and virtually zero when integrator control is employed.
The resulting three-domain control system results in a power bus which is always constant, irrespective of the sun/eclipse status, and is capable (owing to the automatic sequence of the regulators) of delivering peak power to the user via the BDR and batteries without any bus voltage variation. This type of system is suitable for all mission applications.
This type of controller is usually a majority voting concept to eliminate all single point failures which could lead to loss of the bus regulation, and must be as autonomous as possible of all other signals (e.g. clock signals and auxiliary supply voltages).

3.1.3 Conductance control

In 1977, a major breakthrough in power regulator design was made when it was discovered that, by incorporating an inner current or conductance control loop in all power module designs, power modules could be paralleled like building blocks. Moreover, the control loop was of a 'fist-order' rather than a 'second-order' nature, as was state of the art at that time, resulting in simple control-loop design and improved dynamic response. The basic principle is detailed on fig. 6, in the case of a buck power cell, which enters in the power conditioning system as an interface regulator between the battery and the regulated bus.

The novel feature of conductance control is seen as the introduction of a current measurement (R_s) and a second error amplifier (A_2), forming an inner feedback loop, which controls the inductor current (i) as a direct function of the voltage error amplifier output signal (v_c)

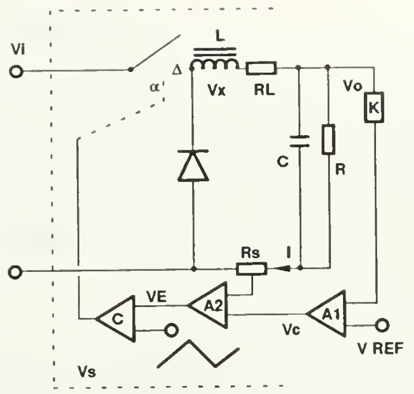


Fig. 6: PWM conductance-control buck regulator

The elements shown inside the box in Figure 3 represent the PWM conductance module (G), which may be paralleled with other similar modules. Regulators operating with this principle can control their inductor currents according to the relation:

$$i = GV_c \qquad (3.5)$$

This feature which applies as well to a buck and a boost regulator which enter in the concepts of BCR and BDR extends to large power applications the regulated bus topology by its power sharing and current limitation capabilities.

3.1.4 Temperature derivative battery management

The objective of state of the art power conditioning remains in its constant research to make the most efficient use of the energy sources. The battery management, as it envolves sizing of the solar array as battery energy source as well as sizing of the batteries for lifetime requirements constitutes a key point in modern power conditioning. The temperature derivative battery management sets out to achieve a technique for precise end of charge termination, so that battery behaviour is predictable, and so that about 30% less solar array charging power is required as compared to the conventional approach.
Use is made of a known property of Ni-Cd and $Ni\text{-}H_2$ batteries. According to this property, the temperature of Ni-Cd batteries increases during discharge and decreases during charge until the end of charge, when the temperature increases, as it is shown on figure 7 where is plotted the battery temperature versus charge time.

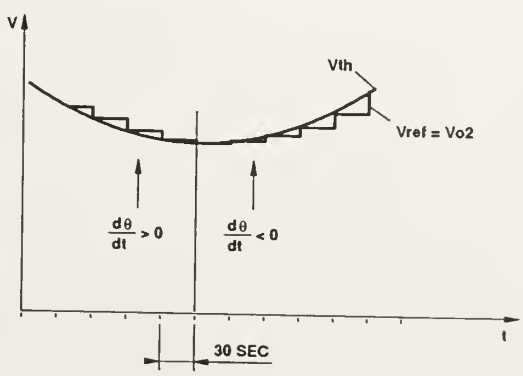


Fig. 7: Temperature derivative principle for battery charge prediction

The accurate prediction of the battery end of charge is realised by detecting the sign change of the battery temperature sample data.

3.1.5 Sequential switching shunt regulator

The essential principle of this regulator, shown in figure 7 bis is effectively one of limit cycle switching of the switch S across the solar array equivalent current generator I_p, in order to maintain the regulated D.C. voltage V_o at all values of load current I_L less than the array current. The limit-cycling control results in an effective duty cycle α such that

$$I_L = \alpha I_p \qquad (3.6)$$

and the frequency of operation is determined by the resultant charge and discharge of the bus capacitor C, so that frequency f is given by

$$f = \frac{I_p}{C} \frac{\alpha (1 - \alpha)}{(V_H - V_L)} \qquad (3.7)$$

where V_H and V_L are the hysteresis limits set for the limit-cycle control comparator.

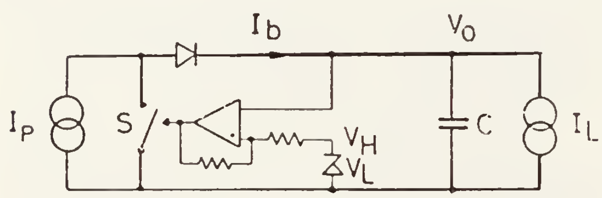


Fig.7 bis: Limit cycle concept

The novel feature of the S^3R is to take the essentially simple principle outlined above and to organise a group of these modules such that they operate sequentially, each one going from zero to 100% duty cycle, prior to the commencement of limit cycling of the next module in the sequence.
This sequence is then controlled as a function of the load demand, with the result that, for a given load condition, only one module is limit-cycling and all others are in a digital state.
The operation of such a regulator is illustrated in figure 7 ter. It is obvious that until the bus voltage approaches the desired regulated voltage, the error signal will be at the lower limit of its dynamic range and hence all module switches will be open, resulting in all array panel currents flowing directly to the bus capacitor and load.
As the error signal responds linearly to the bus voltage the high hysteresis limit (V_{Hn}) are sequentially passed, resulting in closure of the associated switches (S) and a change in the corresponding hysteresis thresholds (V_{Ln}).
This sequential switch closure reduces the current flowing to the bus in steps, until the last switch closure results in insufficient current to match the load current. Due to this deficiency, the bus capacitor discharges, causing a proportional decrease in the error signal (V_e) until the lower hysteresis limit of this module is reached, causing the last switch to open again. Limit cycling will continue between these hysteresis limits for this particular load condition with all other switches in a digital state.

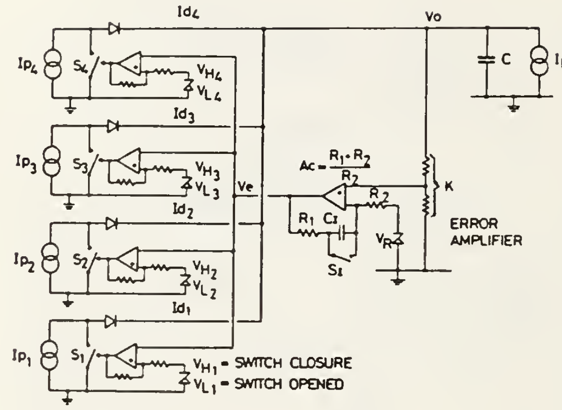


Fig.7ter: S^3R practical approach

3.1.6 Regulated bus voltage amplitude

Several standards exist which define the amplitude of the regulated bus voltage V_o. These standards call to voltages which are trade-offs between conduction losses, copper mass and human safety for ground operations. It is accepted to have the following table:

BUS VOLTAGE	BUS POWER	APPLICATIONS
28 V	< 1 kW	- Meteorology - Scientific
50 V	1 to 5 kW	- Telecom - Vidéo
120 V	> 5 kW	- Space Station

3.2 The low orbit concepts

3.2.1 Satellite applications

High power applications in low orbits involve payloads with pulsed loads generated by on-board radars for Earth observation. The power systems of such spacecrafts must differentiate between constant loads and pulsed loads, in order to avoid conducted noise propagation. A hybrid bus is mandatory, as shown in figure 8 with separate solar array sections associated with their companion switching shunt S^3R sections.
A regulated 50 V bus is generated from m solar array sections, feeding the "quiet" loads of the satellite.
Voltage regulation during power peak demands or eclipses is maintained by n battery discharge conductance controlled regulators (BDR) which link individually each battery to the common bus. These regulators are generally current limited SMART concepts that is a buck push-pull cell to maintain the regulated bus power system configuration, with its attractive features of energy sharing between batteries and overload protection.
The basic difference with the previous configuration is the replacement of the PWM battery charger by a dedicated solar array and shunt sections. This arrangement allows the direct sizing of these solar array sections with the pulsed loads and battery charge requirements as the batteries are particularly stressed both in sunlight as well as in eclipse (30 min every 90 min orbit period). In case of excess of charge, the solar array energy is available via the BDRs to the regulated bus.

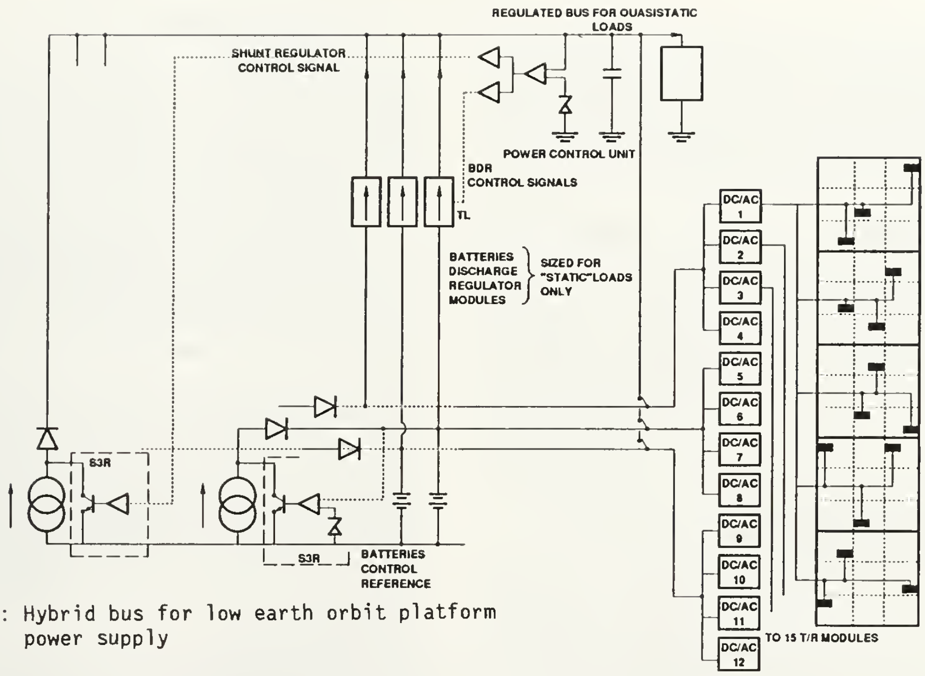


Fig. 8: Hybrid bus for low earth orbit platform power supply

The charge arrays are recommended for a constant current charge mode of individual batteries associated with and end of charge by temperature derivative control.

3.2.2 Space station applications

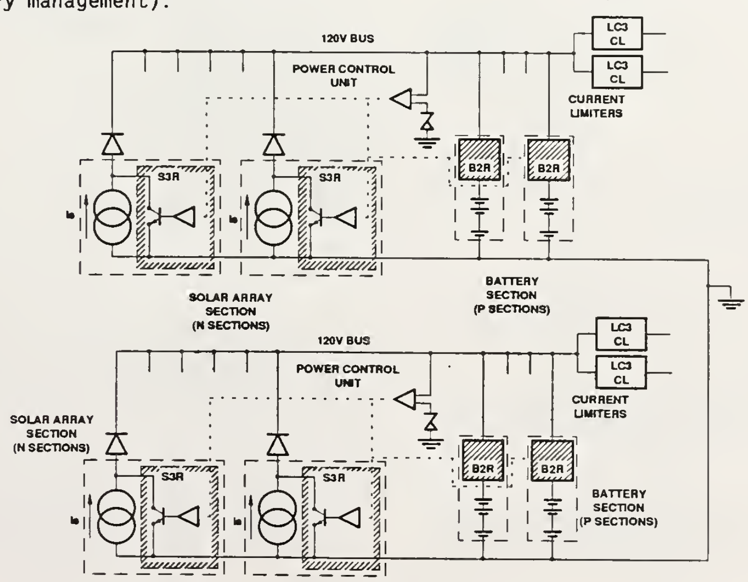
While operating in the low orbit field, the COLUMBUS (European contribution to the International Space Station Programme) power system has the same basic structure as the geostationary configuration. The main differences being:

- The regulated distributed voltage is 120 V instead of 50 V for mass reduction reasons;
- A modular approach at subsystem and system level, due to the large power spectrum requested by the foreseen applications (4.8 kW up to 7.5 kW);
- The types of elements constituting the power system (zero ripple bi-directional Battery Regulator Unit (BRU), Ni-Cd or Ni-H_2 batteries, current controlled PWM switches, temperature derivative battery management).

The basic COLUMBUS power system module is identical to the block diagram shown in figure 9 and has the following features:

SOLAR ARRAY	BATTERY Ni-Cd	BATTERY Ni-H_2	POWER CONDITIONING
10 modules	60 cells	60 cells	- 10 S^3R modules
60 A total nominal mission capability	40 Ah	40 Ah	- 120 V regulated voltage
(150 A max capability)	D = 40% V_{CC} = 1.4 V_{CD} = 1.16 n_B = 75.3 K = 1.10	D = 40% V_{CC} = 1.4 V_{CD} = 1.08 n_B = 67.5 K = 1.14	- 4 Zero ripple module for BRU module 96% BRU efficiency - 20 A PWM switches per distributed network

Fig. 9: Space Station Power Conditioning



Each module is independent and associated to a dedicated electrical user network. In the frame of the ESA program, 2 modules are foreseen for the MTFF (Man Tended Free Flyer) associated with an emergency power bus for essential loads and 2 modules for the PP (Polar Platform) in the configuration shown in figure 9.

4. THE PAYLOAD ELECTRICAL DISTRIBUTION

The user electrical network is constituted by one or several complex payloads generally independent which have to operate simultaneously in good harmony. The objectives of the payload electrical distribution can be grouped in two main areas:

- The interfaces with the platform power system: these electrical interfaces must present no risk of short circuits. Only limited currents for defined durations are tolerated. No electrical pollution from the payload is accepted. This means that the inrush current during load switch-ON and OFF or transients must be severely controlled as well as voltage ripple and noise injected by the payload power supply or any user. Finally the payload electrical network must not induce any current in the satellite structure and grounding harness which could disturb the safe operation of the platform equipments.
- The interfaces with the users: These interfaces are achieved by dedicated power supplies which must act as a buffer between their loads and the rest of the satellite (platform and other users). The power system of the payload plays two roles vis à vis its load. It delivers the right voltages and currents under defined forms of disturbances or noise (ripple impedance protection) and behaves as an active filter against any form of disturbances or noises coming from the plaform, the grounding harness and the other users.

The payloads of a spacecraft belong generally to one of the following two types of payload configurations:

- The complex payload system;
- The multi payload concept.

4.1 The complex payload supply

The electrical power distribution of a payload can be centralised or decentralised, which implies that one or several interfaces will exist between the platform and the users. Several trade-off studies have shown the advantages and disadvantages of these configurations.
Earth observation missions, in low earth orbit, generally consist of complex payload technologies such as Synthetic Aperture Radars (SAR).
On figure 10 is represented such a complex payload constituted by a solid state SAR active array antenna called SAR2000, as it requires 2 KW input power.
The major drawback of active arrays lies in the high number of RF devices (720 radiating elements to be parallelled and operating in a pulsed mode.
The power conditioning and the electrical distribution of such a network have to allow the correct working of the payload in the spacecraft environment as well act as a buffer vis à vis the other payloads and satellite platform which may be sensitive to the noise pollution inherent to a radar operation.
A reduced mass will allow an increase of the mass margin of the satellite that is the availability to extend the lifetime of the mission while reduced power losses not only makes simpler the thermal system but has a direct effect on the platform power system by reducing the area of the solar panels, the weight of the batteries and the power conditioning.
The power distribution is designed to match the reliability requirements which allow the "smooth" loss of some radiating modules without degradation of the RF performances not more than 2% gathered or 10% randomly distributed, for the lifetime mission.
The DC/AC distribution approach is the most attractive concept as it minimises the interfaces with the platform and allow a high level of decentralization towards the users.

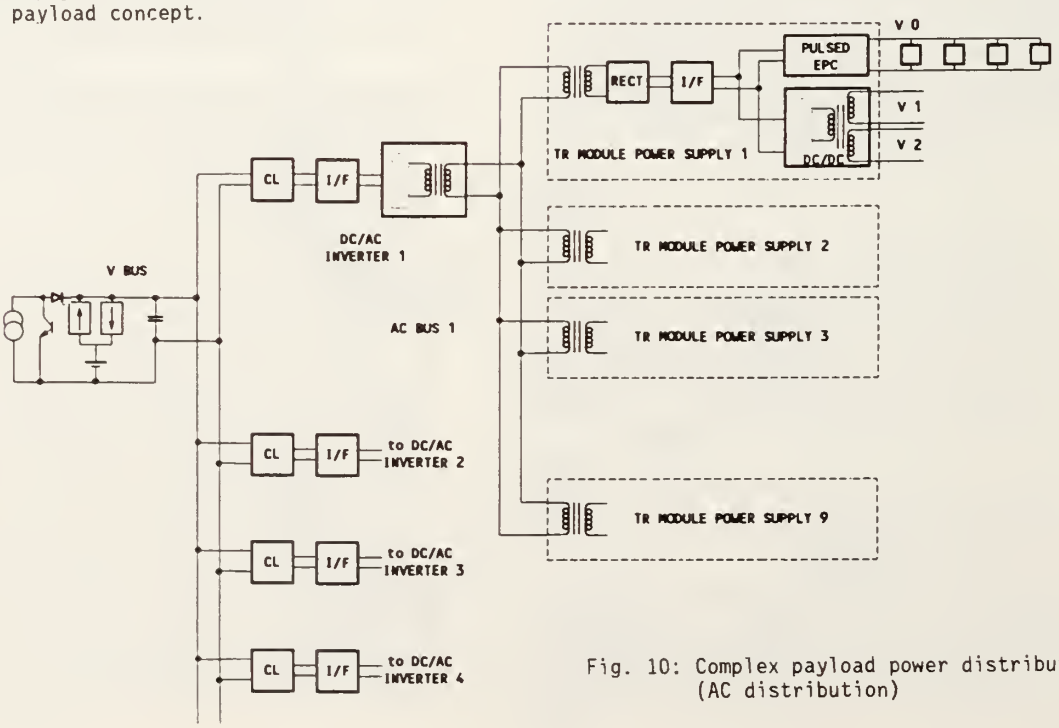


Fig. 10: Complex payload power distribution (AC distribution)

This complex payload involves identical and non redundant power supply modules. Each module is constituted by:
- 9 decentralized TR (Transmitter) modules feeding 4 radiating elements each;
- 45 DC/AC inverters, each one supplying via an AC harness the 9 decentralized power modules.

The interface with the platform bus at 120 V is realized through separate solid state switch current limiters associated with an input filter. This type of payload highlights the essential parts of the electrical distribution concept which are:
- the centralized DC/AC distribution;
- the EMC constraint;
- the solid state switch current limiter.

4.1.2 Centralized DC/AC distribution

The DC/AC centralised distribution involves a slew rate limited square wave inverter interfacing the power bus and feeding through a transformer a distribution harness.

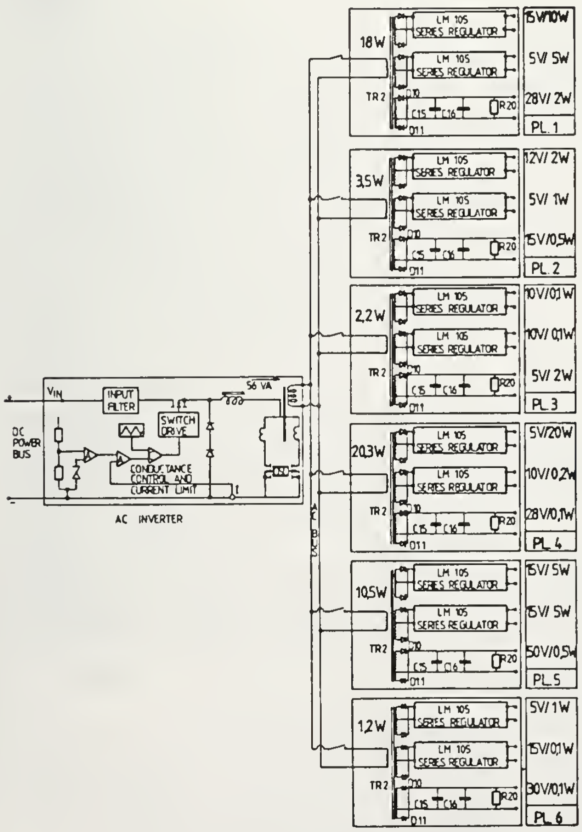


Fig. 11: Exemple of AC powering approach

Each user works out its specific requirements through a dedicate transformer-rectifier-regulation module. An example of such a distribution is detailed on figure 11.

The AC inverter employs conductance control in the PWM control loop in order to provide good dynamic response, rapid current limiting which ensures a reduction in the conducted noise to the central power system and last, but not least, provides instrument failure isolation.

4.1.3 E.M.C. constraints

A complex payload must face the conducted and radiated noise generated by the pulsed voltages and currents. Galvanic insulation between primary and secondary grounds, as shown in figure 12 is mandatory whatever the level of the decentralized topology is.
The electrical distribution harness must involve twisted wires and no DC or AC currents must circulate into the ground structure, as it constitutes a ground reference at spacecraft level.
A grounding topology is detailed on figure 12 where the sum of ground loop currents i_n is such as:

$$\Sigma i_n = 0$$

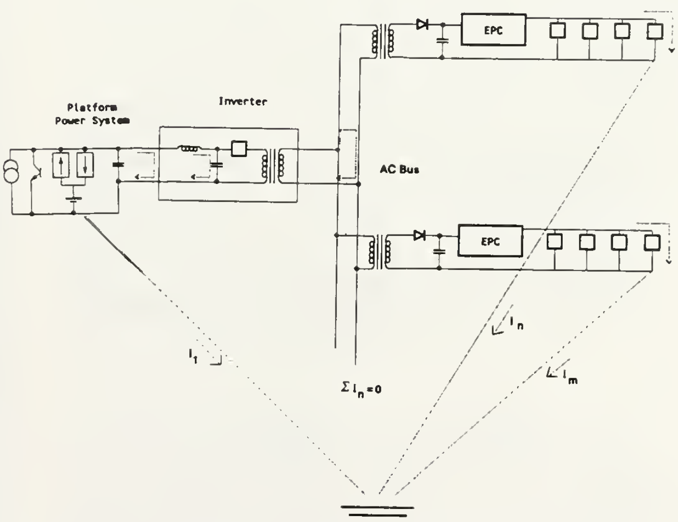


Fig. 12: Grounding concept of a complex payload

4.1.3 Solid state switch current limiter

Electrical distribution within a spacecraft must be protected against load failures and overloading. This means that any failure of a transient or permanent nature must not disturb the nominal operation of the spacecraft.
The current limiter switch is an active device which combines the functions of relay, current limiter and automatic switch. It is particularly important for high power conditioning systems, under the form of a buck power cell associated with a current sensor (LC^3 - Limit cycle conductance control or LC^3 system) or a saturated series regulator.
In both cases, this function presents a fold-back characteristic, depending upon the device temperature as displayed on figure 13.

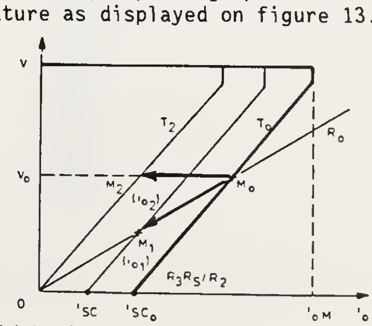


Fig. 13: Fold-back characteristic thermally compensated

4.2 The multipayload concept

The multipayload concept constitutes the most widespread type of application as well as in low and geostationary orbits.
It is composed of several independent payload generally requiring less than 300 W power.
A typical representation of such a configuration is displayed on figure 14 where the spacecraft is constituted by 9 instruments, payload in the frame of a meterological mission.
The electrical distribution utilises a decentralised powering concept. Each user, with its specific requirements, is supplied by means of an independent DC/DC converter. Each converter is supplied from a centralised independent DC/DC converter. Each converter is supplied from a centralised Power Distribution Unit, whose task is to allow dedicated switching of instruments and protection of the power system by means of solid state switch current limiter in event of payload failures. The DC/DC converters consist of conductance controlled Buck regulator feeding a galvanically isolating push-pull power stage.
The reduction of common mode noise interference at instrument level is enhanced by the possibility to individually separate the secondary power grounds to each instrument.

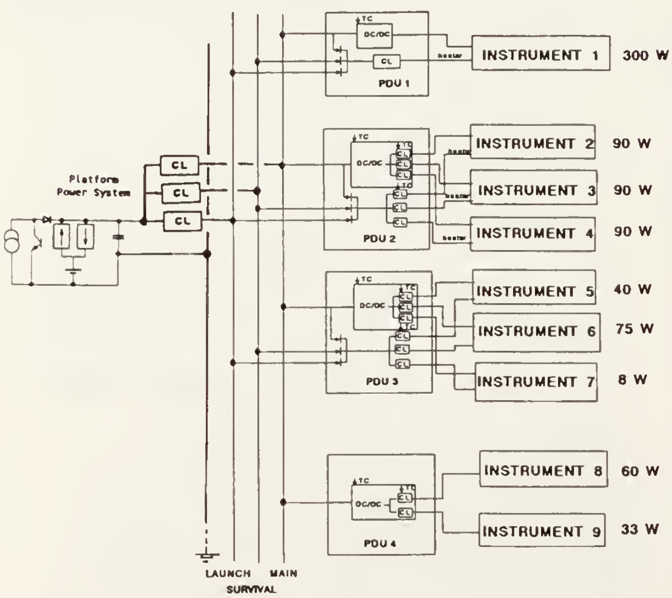


Fig. 14: A multipayload concept

5. CONCLUSION

Future space programs are definitively associated with large spacecrafts required for both automatic platforms or inhabited space stations, with high energy requirements. To satisfy the requirements of flexibility, growth potential and safety, the power systems of such spacecrafts will utilise a regulated bus voltage of 50 V for missions up to 5 kW and 120 V for higher power demands in both single and multibus approaches.
The power conditioning suitable for such large power systems is inevitably modular, composed of several identical modules in parallel, of a switching type to reduce the losses and as autonomous as possible. Their essential objective is that the modules be equivalent to current sources in order to simplify parallel operation of these modules and control the maximum current in event of overloads resulting from equipment failure.
Current controlled modular concepts are therefore a must in advanced power conditioning for high power applications.
The power conditioning has also another important objective. It must physically decouple the energy sources from the electrical user network for two reasons. The first being is to allow the independent management of these sources, such as charge control, reconditioning of batteries or solar array positioning or degradation. The second is to allow their replacement by simple refurbishment or by utilising new technology products such as $Ni\text{-}H_2$ or Na-S for the batteries and Asga for the solar arrays. The system approach adopted for Columbus has been geared to allow replacement and upgrading to new technologies with minimum impact on the unmodified parts of the system, hence, catering for easy servicing and power upgrading. Two types of power conditioning equipment have been described, the S^3R for the regulation of the solar array and the conductance control principle for the battery conditioning.
However the power conditioning concept must not be treated in isolation from its main tasks which are to provide a high quality of voltage regulation to the user, whilst providing essential protection to the central power system. It has been shown that the above objectives can be achieved by implementing, a three domain control concept. The inherent current control operation of these power conditioning module simplifies this interface to a unique control signal.
The payload electrical distribution employs identical concepts to those used in the central power system. The DC/AC and DC/DC regulators use conductance control regulation and protection features to ensure good dynamic performance and fault isolation. The development of the solid-state-switch has been an essential task to eliminate the use of conventional fuse and electromechanical switchgear in order to provide better fault isolation and simpler power bus protection concepts.
Power conditioning for future large power applications has been adapted to the needs of future payloads and by using the state of the art in both technology and human resources has shown that this process will continue, Cinderella can shed tattered gown and become the "belle-of-the-ball".

B4.3 Preliminary Plan for a 20 kW$_e$ space solar "gyroréacteur"

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RESUME.

Cette note présente un nouveau type de moteur thermique, bien adapté aux applications spatiales, parce qu'il demande des surfaces de miroir et de radiateur très inférieures à celles des machines à cycles de JOULE, voire de STIRLING.
Les excellentes performances de tels "gyroréacteurs" sont dues à l'utilisation de champs artificiels de gravitation dans des échangeurs lamellaires en rotation, dont la technologie a pu être développée, en vue des premières expérimentations.

ABSTRACT

This paper proposes a new concept of thermal engine, well suited to space power systems, as it needs much less concentrator and radiator surfaces than in BRAYTON or even STERLING cycle engines. Outstanding efficiencies can be obtained with the so-called "gyroreactors", using artificial gravitational fields and lamellate rotating heat-exchangers; the technology of such components was developed for prototype experiments.

INTRODUCTION.

Le rotor présenté en coupe axiale sur la figure I constitue l'organe essentiel d'un moteur thermique, qui peut être désigné sous le terme générique de "gyroréacteur spatial":

L'armature mécanique de ce rotor est un assemblage rigide de disques de forte épaisseur, supportant un circuit fermé de xénon sous pression. Le gaz se déplace dans ce circuit, avec des vitesses relatives très inférieures aux vitesses d'entrainement du rotor, entre un échangeur central de source froide et des éléments chauffants périphériques. La chaleur utilisée provient directement de l'énergie radiative du soleil, concentrée par des miroirs fixes et directement absorbée par des collecteurs entrainés en rotation avec le circuit.

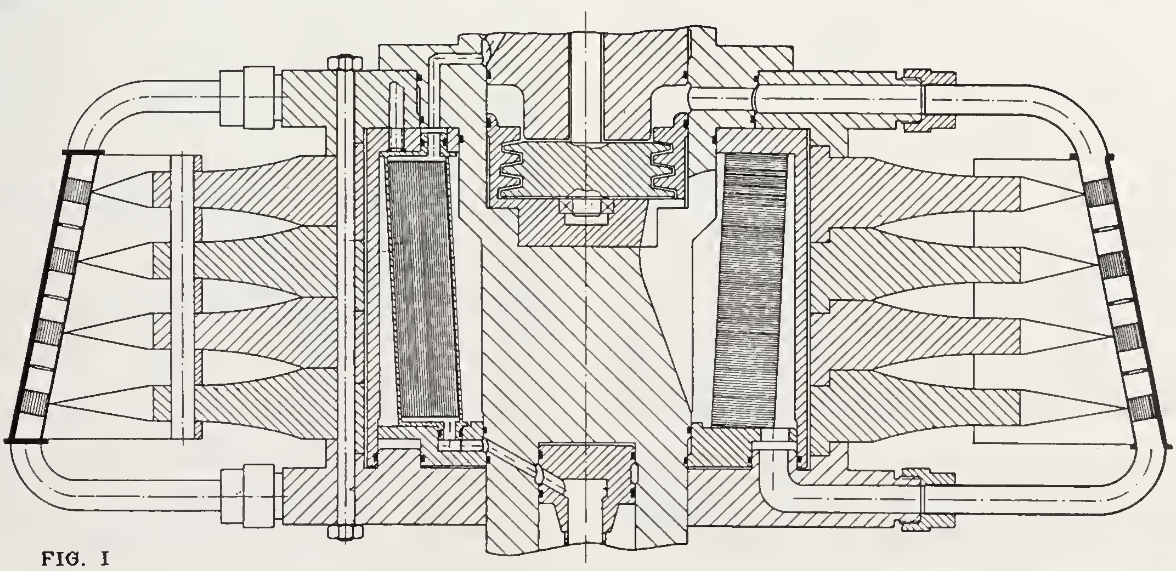

FIG. I

D'un point de vue physique, on observera que l'utilisation d'échangeurs en rotation à écoulement radial permet de réaliser n'importe quelle évolution polytropique d'un gaz parfait, avec des pertes beaucoup plus faibles que dans les machines adiabatiques classiques, qui comportent des grilles d'aubes où se dégrade inévitablement prés de 10 % des échanges d'enthalpie mécanique.

D'un point de vue technologique, la conception de tels rotors et de leur pivoterie relève surtout de matériaux et de procédés aujourd'hui bien maitrisés.

La question cruciale concerne la réalisation pratique d'échangeurs dans lesquels le diamétre hydraulique des conduits du gaz lourd utilisé, mauvais conducteur de la chaleur, ne dépasse pas une fraction de millimétre. Les problèmes d'encrassement et de corrosion, qui ne se posent plus avec des gaz neutres, proscrivent en effet, dans les échangeurs habituels, l'utilisation de surfaces de transfert aussi fractionnées.

Un programme ad hoc de développement a donc été entrepris, sous l'égide de l'AGENCE FRANCAISE POUR LA MAITRISE DE L'ENERGIE.

Ce programme a permis de mettre au point des procédés élaborés de fabrication de modules lamellaires, à partir de feuilles de cuivre de 0,1 mm d'épaisseur et de 10 mm de largeur, dûment entretoisées et brasées perpendiculairement à des plaques de 1 mm d'épaisseur. Ces procédés ne sont pas encore développés jusqu'au stade industriel, mais ils conviennent d'ores et déjà pour réaliser des dispositifs expérimentaux et des prototypes.

Les gyroréacteurs en question peuvent, par conséquent, entrer désormais en compétition avec d'autres moteurs thermiques et pompes à chaleur terrestres.

Leur utilisation comme moteurs solaires spatiaux s'accompagne en outre de simplifications notables:

- Il n'y a plus besoin d'aménager une enceinte de confinement pour limiter les frottements.

- Et surtout, il n'est plus nécessaire d'incorporer dans le rotor un second circuit caloporteur, comme on est obligé de le faire, lorsque la chaleur utilisée est libérée en dehors du rotor.

PRINCIPE GENERAL DE FONCTIONNEMENT.

Le principe de fonctionnement d'un tel "gyroréacteur solaire spatial" n'est autre que celui qui est à l'origine des mouvements de l'atmosphère des planétes:

- On sait que les gaz sont réchauffés au voisinage du sol, (jouant le rôle de collecteur solaire), puis refroidis dans les couches stratosphériques, (jouant le rôle de radiateur spatial).

- Le champ conservatif de la pesanteur locale, (de même que le champ artificiel de gravitation dans le rotor que nous envisageons), n'intervient pas dans les bilans énergétiques globaux des processus en cause.

- Mais il en est le catalyseur indispensable, puisqu'il assure la majeure partie des "turbocompressions" du fluide de travail, avec emprunt et restitution exacte de l'énergie potentielle du champ, échangée de façon quasiréversible avec l'énergie interne du fluide.

Il est clair, d'autre part, que les dénivellations de températures obtenues sont inversement proportionnelles aux chaleurs spécifiques; d'où l'intérêt d'un gaz aussi lourd que le xénon, dont le prix, relativement élevé, n'est pas dissuasif pour des applications spatiales.

AVANTAGES ESCOMPTES.

1/ La machine présentée est loin d'épuiser les possibilités des alliages réfractaires maintenant utilisés en aéronautique, puisqu'on a limité à 850° K la température du gaz.

Son rendement, lorsque la température la plus basse est fixée à 330 °K, est pourtant de l'ordre de 45 %, c'est-à-dire trois fois plus que le rendement du cycle simple des turbines à gaz classiques, si on devait les utiliser dans le même intervalle de températures. Cet écart des rendements diminue évidemment, lorsque l'intervalle des températures extrêmes s'élargit; mais il reste trés substantiel, même vis-à-vis des performances éspérées pour les cycles de de STIRLING.

2/ D'autre part, le flux radiatif moyen que nous avons pris en considération, soit 40 watts par cm^2, reste en deçà de ce que permettraient des systèmes de concentration perfectionnés. Cette valeur modérée est cependant compatible avec une puissance éléctrique déjà appréciable de 400 watts par kilog de rotor. D'où une masse spécifique du générateur, en y incluant tous les composants du système, trés inférieure à ce qu'on peut éspérer avec des réacteurs nucléaires spatiaux à fission, même pour des puissances supérieures au Mégawatt.

Comparées à celles des autres systémes dynamiques connus, les performances de rendement et de puissance spécifique de l'avant projet présenté, qui n'est que l'esquisse préliminaire et assez rustique d'un gyroréacteur spatial répondant à une mission bien définie, méritent par conséquent de retenir l'attention: Elles ouvrent la voie à des réductions considérables:

- de l'encombrement du concentrateur solaire,
- de la masse du convertisseur proprement dit
- et, singuliérement, de la part dévolue au radiateur de source froide, dans la masse totale du générateur.

DOMAINE DES PUISSANCES COUVERTES PAR CE TYPE DE CONVERTISSEUR.

La puissance du prototype présenté a été fixée à 20 kwe, pour la situer au seuil d'un domaine de puissance unitaire au delà duquel la simplicité des générateurs photovoltaïques ne compense pas forcément leur modeste rendement.

Des machines similaires pourraient répondre efficacement aux besoins de stations ou engins spatiaux dans une gamme de générateurs allant de 5 à 1000 kwe.

Il n'est pas exclu que l'extrapolation de la taille des rotors et l'augmentation de leur puissance volumique se justifie au delà du mégawatt, tant la technologie et les conditions d'emploi des générateurs nucléaires à très haute température restent onéreuses dans la phase du développement et précaires au stade de l'utilisation.

Mais il est vraisemblable que d'éventuelles centrales de grande puissance s'accomoderaient plus aisément d'un assemblage de générateurs modulaires.

En contrepartie, le système proposé, de même les convertisseurs photovoltaïques, n'est pas compatible avec un stockage thermique de l'énergie; le maintien de la puissance fournie dans les zones d'ombre proches de la terre implique un stockage éléctrochimique ou inertiel.

REMARQUE LIMINAIRE.

L'importance des avantages ainsi évoqués amène à se demander pourquoi de tels dispositifs, qui ne sont, en définitive, qu'une application du théoréme de BERNOUILLI généralisé, sont restés si longtemps méconnus.

Plusieurs suggestions dans ce sens ont pourtant été présentées depuis le début du siècle, notamment, parait-il, par le physicien NERNST; mais elles n'ont pas été retenues. Les raisons en sont, semble-t'il, les suivantes:

1/ Les fluides compressibles d'usage industriel courant, vapeur d'eau ou gaz de combustion dans l'air, ont des chaleurs spécifiques trop élevées pour que les vitesses périphériques de rotors facilement réalisables conduisent à des des écarts adiabatiques de température suffisanmment élevés.

2/ Comme on l'a déjà dit, les échangeurs tournants adaptés à des gaz lourds ne peuvent pas se fabriquer par des techniques industrielles triviales.

3/ La plupart des configurations envisagées ne permettaient pas un arbitrage satisfaisant entre les autres contraintes technologiques et les exigences de la thermodynamique.

4/ Enfin et surtout, le coût très bas des moteurs thermiques classiques, après plus d'un siécle d'améliorations remarquables, ne justifiait pas, jusqu'à maintenant de telles innovations industrielles, dans un contexte énergétique favorable.

OBSERVATIONS RELATIVES AUX VALEURS EXCEPTIONNELLEMENT ELEVEES DU RENDEMENT.

Trois raisons fondamentales expliquent les valeurs a priori surprenantes des rendements revendiqués plus haut:

1/ Comme on peut s'en convaincre en examinant le bilan thermodynamique originel de l'énergie éolienne, ou la part imputable à la seule compression rotorique dans les pertes des compresseurs centrifuges, (dès lors que des précautions sont prises pour contrôler les effets gyroscopiques, qui ne sont pas intrinsèquement dissipatifs, mais peuvent induire des distorsions d'écoulement nuisibles, aux faibles débits), la compression et la détente dans un champ de forces massiques peuvent se faire sans avoir à consentir le taux élevé de pertes irréductibles, qui constitue le handicap majeur des cycles dits de JOULE ou de BRAYTON.

2/ Les apports ou les retraits d'enthalpie thermique, dans un échangeur en rotation, peuvent être compensés par des retraits ou des apports d'enthalpie mécanique, prélevée sur le champ de forces, pour aboutir, si on le désire, à des "échauffements" et des "refroidissements "proches de l'isotherme.

3/ Bien que cette condition essentielle soit souvent méconnue dans les propositions de machines thermiques nouvelles qui n'ont pas subi la sanction de l'expérience, il importe, au surplus, que la vitesse débitante V, dans les échangeurs, ne s'écarte pas beaucoup de la valeur fournie par la relation:

$$V^2 T / C_p \theta^2 = 2\, \mathcal{S}t / \mathcal{C}f$$

dans laquelle T est la température absolue, θ l'écart de température gaz-paroi et ou, sous certaines réserves, le rapport $2\mathcal{S}t/\mathcal{C}f$ du nombre de STANTON au coéfficient de frottement reste de l'ordre de l'unité, pour un écoulement laminaire, comme pour un écoulement turbulent.

Cette relation, qui traduit un arbitrage un peu plus favorable au rendement qu'à la puissance spécifique, impose des contraintes strictes aux configurations choisies, pour une densité donnée du fluide de travail.

PHYSIQUE DES TRANSFERTS DANS DES CONDUITS ENTRAINES EN ROTATION.

Alors que, dans des circuits immobiles et pour de faibles nombres de MACH, les coéfficients d'échange de chaleur et de frottement ne dépendent que du nombre

de REYNOLDS et du nombre de PRANDT, il faut tenir compte, au surplus, dans des conduits entrainés en rotation, de deux paramètres d'échelle supplémentaires, rendant compte de l'influence des forces d'ARCHIMEDE et des forces de CORIOLIS.

On a donc affaire à une aérodyamique où le comportement des couches limites dépend des trois paramètres $\mathcal{R}e$, $\mathcal{R}a$ et $\mathcal{R}o$, de REYNOLDS, de RAYLEIGH et de ROSSBY, définis de la façon suivante en fonction de la vitesse V, de la viscosité cinématique μ/ρ, de la pesanteur locale $\omega^2 r$, de l'écart de température avec les parois θ, du coéfficient de dilatation 1/T et de la distance e entre deux parois planes et parallèles:

$$\mathcal{R}e=2\rho Ve/\mu;\ \mathcal{R}a=8e^3\rho^2\omega^2 r\theta/\mu^2 T \text{ et } \mathcal{R}o=V/2e\omega$$

Cette multiplicité de paramètres donne lieu à des structures dissipatives d'une richesse extrême, comparable à celle des phénomènes météorologiques, dont l'étude théorique et expérimentale ne présenterait pas moins d'intérêt que celle des tourbillons dits de BENARD.

Pour les besoins pratiques immédiats, il se trouve heureusement que l'utilisation de lames très minces permet de négliger les transitoires à l'entrée du gaz et de s'en tenir au régime asymptotique, qui se prête à une solution exacte des équations classiques, avec une seule variable d'espace et les deux composantes u et v d'un vecteur vitesse parallèle aux parois.

L'application d'un opérateur différentiel linéaire du 6° ordre à la fonction complexe z = u + i.v fournit ainsi la distribution des vitesses, valable pour un domaine laminaire qui peut s'étendre bien au delà de la valeur 2000 du nombre de REYNOLDS, si l'écoulement correspond bien à un "réchauffement ascendant", ou à un "refroidissement descendant".

Les distributions les plus générales sont une combinaison des vrillages "géostrophiques" dus aux forces de CORIOLIS et des bourrelets latéraux dus aux forces d'ARCHIMEDE.On obtient ainsi les coéfficients de transfert cherchés, en fonction des 3 nombres d'EKMAN ($\mathcal{R}e/\mathcal{R}o$), de GRASHOF ($\mathcal{R}a/\mathcal{P}r$), et de REYNOLDS, des 3 angles définissant l'orientation des conduits et celle des parois et, éventuellement, du gradient transversal de la température.

On constate d'ailleurs, à cette occasion, qu'il convient de définir deux valeurs distinctes pour chacun des nombres de NUSSELT et de DARCY, suivant qu'on s'intéresse aux coéfficients moyens de transfert, définis par des intégrales sur les écarts de température et de vitesse, ou aux coéfficients de dégradation thermodynamique, définis par des intégrales sur les carrés de ces écarts.

Pour les besoins du présent avant-projet, les paramètres nécessaires peuvent aussi se déduire de valeurs expérimentales tirées de la littérature relative à des écoulements mixtes comparables.

EVOLUTION DU FLUIDE DE TRAVAIL.

Le xénon utilisé contient un peu d'hélium, dans la proportion de 3 mg/g, ce qui augmente la conductivité de 70 % et la chaleur spécifique de seulement 10 %.

Pour des contraintes externes arbitraires, l'évolution de la températur absolue T(r), généralement somme d'un terme exponentiel et d'un polynôme du second degré, se calcule facilement, dans chaque branche du circuit fermé, à partir des coéfficients de transfert locaux. La dernière constante d'intégration se détermine par la relation:

$$\omega^2 \oint r.dr/T(r) = \Sigma_i \delta S_i$$

où les δS_i sont les augmentations locales de l'entropie spécifique, dues aux frottements et aux pertes de la turbine.

Le régime nominal correspond à de conditions ajustées pour obtenir des évolutions "polytropiques", avec des échanges de chaleur proportionnels à ω^2r.dr. Le diagramme T(S) est alors représenté par la figure II, les pressions, vitesses et diamètres hydrauliques étant explicitées en annexe, en fonction des distances r.

EVOLUTION DE LA TEMPERATURE AU REGIME NOMINAL

en fonction de l'entropie S : ————

en fonction du champ centrifuge $\omega^2 r^2/2C_p$: --------

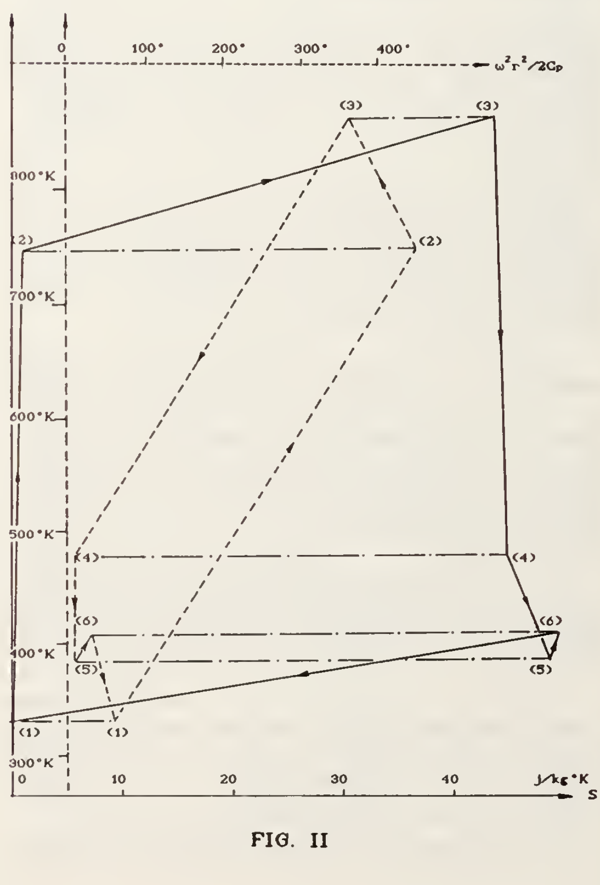

FIG. II

AGENCEMENT MECANIQUE DU ROTOR.

La figure III montre une coupe axiale de l'ensemble du rotor, qui tourne dans le vide, soutenu et guidé dans un support fixe, (qui n'est représenté que très partiellement), par une butée magnétique 3 et deux paliers magnétiques actifs 4.

Cette figure permet de repérer les dessins rassemblés à la dernière page:

- Coupes frontales A, A' de la figure IV,

- Coupes frontales B et B' de la figure VI,

- Figures V et VIII, représentant les éléments chauffants 5 et les échangeurs de source froide 6.

- Figure VII montrant un détail des garnitures d'étanchéité 1 et 2, ainsi que l'extrémité de l'axe lié au corps statorique de la turbine 7 et l'orifice 8, qui permet de modifier la quantité de gaz présent dans le circuit.

Les tableaux de l'avant-dernière page précisent, d'autre part, les principales caractéristiques géométriques et physiques de cet avant-projet.

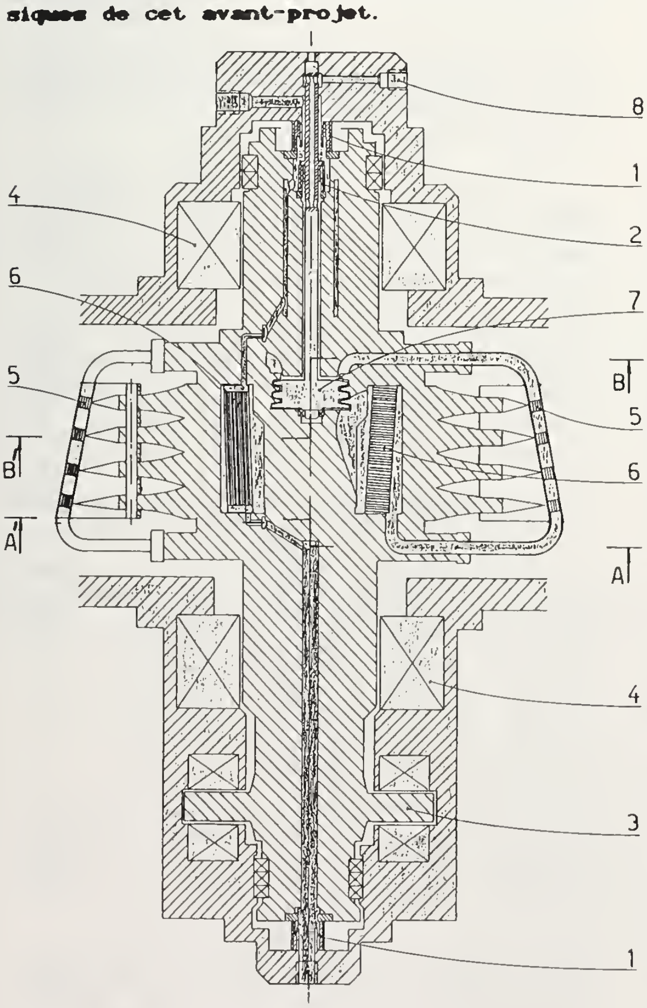

FIG. III

La structure mécanique du rotor s'organise autour d'un arbre cylindrique de grand diamètre, qui est refroidi sur toute sa longueur par la circuit secondaire de l'échangeur et à l'intérieur duquel s'insère le carter de la turbine:

Circuits adiabatiques.

Les conduits radiaux de compression et de détente sont soudés, par une extrémité coudée, aux 24 éléments chauffants, librement dilatables dans les directions radiale et axiale. Ils sont d'autre part raccordés à leur autre extrémité, par des joints d'étanchéïtés démontables, à des armatures circulaires, qui supportent leur charge centrifuge et canalisent le fluide de travail, dans les perforations qui y sont ménagées.

Les éléments chauffants sont eux-mêmes supportés par quatre disques massifs, suivant une technique tout à fait semblable à celle qui est utilisée pour les disques de turbines classiques, aussi bien pour ce qui concerne les alliages utilisés, que l'évolution radiale de leur épaisseur et le mode de liaison avec les organes périphériques à supporter. Dans le moteur décrit, cette liaison se fait par de simples clavettes.
Ces disques, centrés entre eux et vis à vis des deux armatures latérales par des épaulements circulaires, sont solidarisés par frettage et par des tirants parallèles à l'axe, de sorte que l'ensemble constitue un bloc trés rigide, dont la vitesse critique est très supérieure à la vitesse nominale de rotation.

Eléments chauffants.

Chacun des éléments chauffants, dont un détail est représenté sur la figure V, comporte un secteur troncônique, rigidifié par des entretoises frontales,

- dont la face tournée vers l'extérieur est constituée par une plaque collectrice en cuivre oxydé, qui absorbe la chaleur apportée par le rayonnement et la transmet par conductivité vers des blocs lamellaires en contact avec le gaz.

- dont les extrémités sont soudées aux tubulures radiales démontables,

- dont les faces latérales sont soudées aux extrémités d'étriers, constitués par une tôle profilée en alliage réfractaire à très haute résistance, qui enjambent les clavettes de liaison, de part et d'autre des disques.

Les blocs lamellaires sont découpés par usinage électrolytique dans des empilements de lames minces de cuivre, ajourées par moletage ou par étirage, puis raccordés aux plaques collectrices par brasage dur. Leur fractionnement en quatre segments dans la direction axiale permet d'augmenter la puissance volumique locale et de réduire la masse totale supportée par les disques.

Turbine.

Le corps interne de la turbine est maintenu immobile par un axe fixe, muni d'une garniture d'étanchéïté.

Les aubages sont ceux d'une turbine axiale classique, à trois étages à action, pour un nombre de REYNOLDS de 2.10^6 et un nombre de MACH de 0,6.

Des saignées radiales fraisées dans le diffuseur de sortie, distribuent le xénon dans l'échangeur de source froide.

Echangeur de source froide.

Les 12 secteurs de l'échangeur de source froide, à écoulements croisés, s'appuient sur une virole cylindrique, logée dans l'alésage des disques résistants, dont le fond est vissé sur le support du carter de turbine.

Le xénon circule entre des lames de cuivre ajourées de 0,4 mm d'épaisseur, disposées de part et d'autre des conduits nervurés de l'eau, qui sont légèrement inclinés sur l'axe de rotation, pour éviter les ressauts pouvant nuire à la purge des bulles de gaz occlus.

Tant que la vitesse de l'eau ne dépasse pas 5 m/s, sa circulation peut se faire spontanément par thermosiphon, (outre le pompage réactif, à l'entrée du rotor).

Dispositifs d'étanchéïté.

L'assemblage initial des différents organes requiert la mise en oeuvre de joints toriques, dont la plupart peuvent être remplacés par des soudures définitives, s'agissant d'équipements spatiaux non récupérables.

La connection des circuits mobiles avec les organes fixes se fait au moyen de garniture mécaniques d'étanchéïté, dont le comportement peut assurer au générateur une grande longévité, puisqu'elles sont bien refroidies et que les vitesses de glissement y sont au moins trois fois plus faibles que celles des bagues qu'on sait réaliser dans l'industrie nucléaire.

Paliers magnétiques.

Comme leur alésage est très largement dimensionné, pour permettre le montage et le démontage de la turbine, les paliers et la butée magnétiques, de type standard, ne supportent que des efforts radiaux et axiaux très inférieurs aux normes admises.

VIBRATIONS.

Du fait de la compacité et de la grande rigidité du système, son comportement vibratoire global ne pose pas de problèmes particuliers.

Les tubulures radiales ayant, d'autre part, une fréquence propre de vibration relativement basse, et bien que les forces d'excitation internes soient considérablement plus faibles que dans les aubages de turbine, il peut être opportun de les munir de dispositifs amortisseurs ne nuisant pas à la libre dilatation des éléments chauffants.

DEMARRAGE.

Ce moteur pourrait, en principe, fonctionner avec une circulation rétrograde du fluide de travail, d'où résulterait une augmentation des gradients radiaux et axiaux de température et, corrélativement, une aggravation des phénomènes de pontage thermique (qui restent tout à fait acceptables dans le mode normal de fonctionnement). Mais on peut facilement l'éviter, au moyen d'une procédure de démarrage appropriée.

VARIANTES.

Le convertisseur d'énergie solaire présenté, dont les principales dispositions font l'objet d'une protection par brevet et dont la technologie a été suffisamment simplifiée pour qu'il puisse faire l'objet d'un développement immédiat, comporte de nombreuses variantes, laissant envisager de nouvelles améliorations du rendement et (ou) de la puissance massique et de la puissance unitaire.

Sa puissance peut déjà être portée de 30 à 50 kwe, en modifiant la hiérarchie des températures, sans changer la vitesse périphérique. Mais on peut aussi :

- pour éviter les sujétions dues à l'emploi de l'eau comme fluide secondaire de source froide, utiliser un gaz léger comme l'hydrogène ou l'hélium, avec un écoulement centripète, à contre-courant,

pour les rotors de grande taille, délivrant une puissance de plusieurs Mwe, utiliser les mouvements convectifs spontanés d'un métal liquide pour transférer la chaleur entre les collecteurs de rayonnement et les "corps de chauffe",

- améliorer l'efficacité du couplage moteur au moyen d'une turbine centripète,

- nonobstant l'influence éventuelle des forces de VAN DER WALS, réduire la chaleur spécifique du gaz au moyen d'aéorosols très submicroniques de métaux ayant une masse atomique très élevée,

On peut en outre envisager, avec, bien entendu, des exigences complémentaires de développement technologique:

- une augmentation des vitesses périphériques, en remplaçant l'alliage ferritique des disques par des alliages de titane et (ou) le cuivre des lames chaudes par des alliages de béryllium

- et bien d'autres dispositions constructives, qui ne peuvent pas être évoquées dans le cadre de ce bref exposé introductif.

LISTE DES PRINCIPAUX PARAMETRES.

POUR UNE PUISSANCE MECANIQUE NOMINALE DE 20 KW
avec une vitesse de 20'000 tr/min
et un flux radiatif de 40 w/cm^2

(La puissance du même moteur peut être portée à 50 kw, avec une vitesse de 15'000 tr/min, si on dispose d'un flux radiatif de 136 w/cm^2)

1. ENCOMBREMENT ET POIDS.

surface irradiée	1075 cm^2
avec un diamètre moyen de	380 mm
distance entre les deux faces latérales du rotor	160 mm
longueur de la pivoterie (sans les alternateurs)	700 mm
poids approximatif du rotor	50 kg

2. BILAN ENERGETIQUE. (à 20'000 tr/m)

puissance radiative	46,25 kw
pertes par conduction directe	1,85 kw
frottements (échangeurs, garnitures, etc)	1,10 kw
pertes de la turbine	2,50 kw
puissance mécanique développée	20 kw

3. FLUIDE DE TRAVAIL.

Xénon contenant 0,3 % en poids d'hélium, sous une pression variant entre 5 et 50 bars, au régime nominal

4. ELEMENTS CHAUFFANTS.

épaisseur des lames de cuivre	0,2 mm
diamètre hydraulique	0,19 mm
largeur des ailetages	8 mm
volume total des 24×4 éléments	230 cm^3
distance à l'axe de rotation	195 à 175 mm
chute de température dans le cuivre	18°
chute moyenne de température cuivre-gaz	12°

5. ECHANGEUR GAZ-EAU.

diamètre intérieur de la virole	144 mm
épaisseur de la virole	4 mm
côté gaz :	
épaisseur de lames de cuivre	0,4 mm
diamètre hydraulique	0,27 mm
largeur des 12×2 ailetages	6 à 14 mm
distance à l'axe variant de	40 à 65 mm
chute de température dans le cuivre	7°
chute de température gaz-cuivre	25°
côté eau :	
diamètre hydraulique	1,5 mm
chute de température cuivre-eau	13°

6. TURBINE.

trois étages à action, avec une vitesse relative de	60 m/s
vitesse débitante à la sortie	45 m/s
hauteur relative des aubages	0,4
nombre de MACH	0,6
nombre de REYNOLDS	2×10^6

7. DISQUES SUPPORTS.

diamètre extérieur	300 mm
alésage	156 mm
épaisseur au niveau des clavetages	12,5 mm
épaisseur en deçà de ϕ = 198	25 mm
contrainte maximale	800 MPa
diamètre des tirants de liaison	6 mm
diamètre des clavettes	8 mm

8. TUBULURES RADIALES

diamètre intérieur	10 mm
épaisseur moyenne	0,5 mm
diamètre de raccordement aux roues latérales	250 mm

9. PIVOTERIE.

diamètre de raccordement au collecteur froid	70 mm
diamètre de raccordement au collecteur chaud	118 mm
diamètre de raccordement au corps de turbine	80 mm
diamètre externe des cloisons du diffuseur de gaz	80 à 96 mm
diamètre moyen des garnitures fixes eau-vide	26 mm
diamère de la garniture eau-gaz	15 mm

10. EVOLUTION DU FLUIDE DE TRAVAIL.

1 - Sortie de l'échangeur.
2 - Début de l'échauffement.
3 - Fin de l'échauffement.
4 - Entrée dans la turbine.
5 - Sortie de la turbine.
6 - Début du refroidissement.

(n)	1	2	3	4	5	6
$r\times10^3$(m)	67,5	195	175	28	28	42,5
T(°K)	330	746	846	476	386	398
t(°C)	57	473	573	203	113	125
p(bars)	6,40	48,69	36,24	8,49	4,57	5,58
$\rho\times$(kg/m^3)	31,5	106,0	69,6	29,0	19,2	22,8
S(j/kg°K)	0	0,7	43,8	44,7	48,7	49,1
$s\times10^4$(m^2)	17	23	17	13	40	80
$\delta\times10^3$(m)	3	0,19	3	3	5	0,27
V(m/s)	11	6,7	13	40	15	6,5

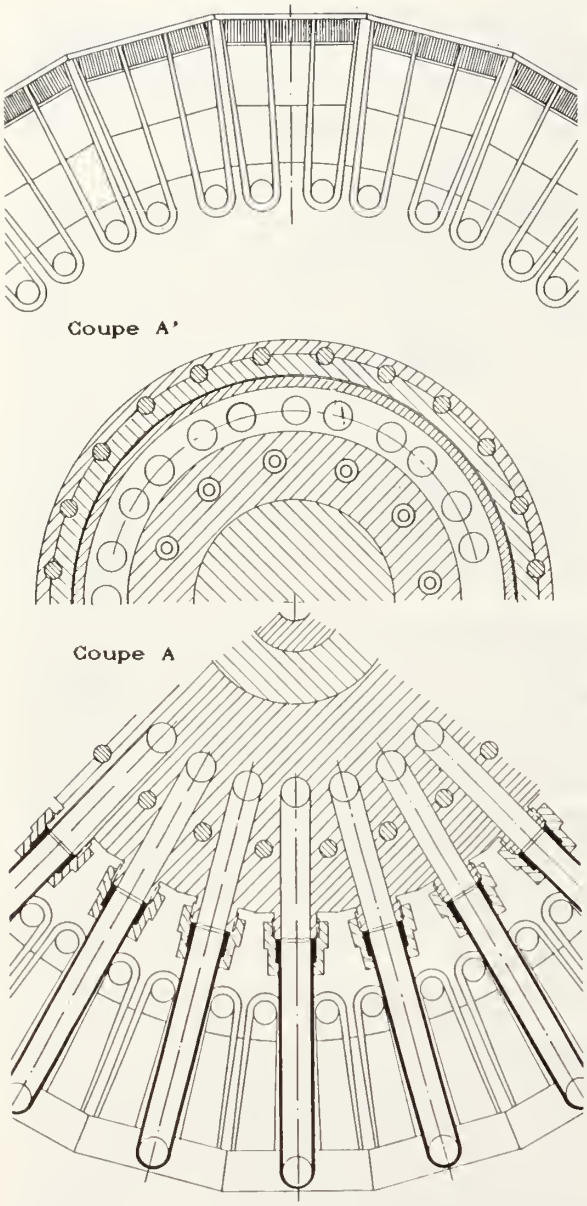

FIG. IV

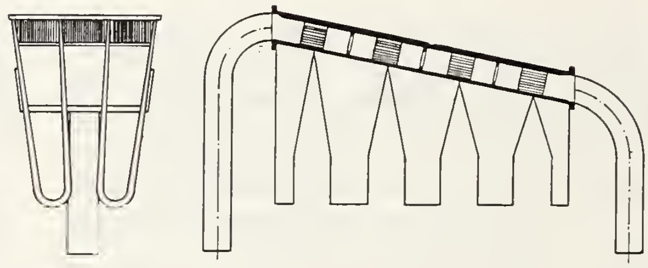

FIG. V

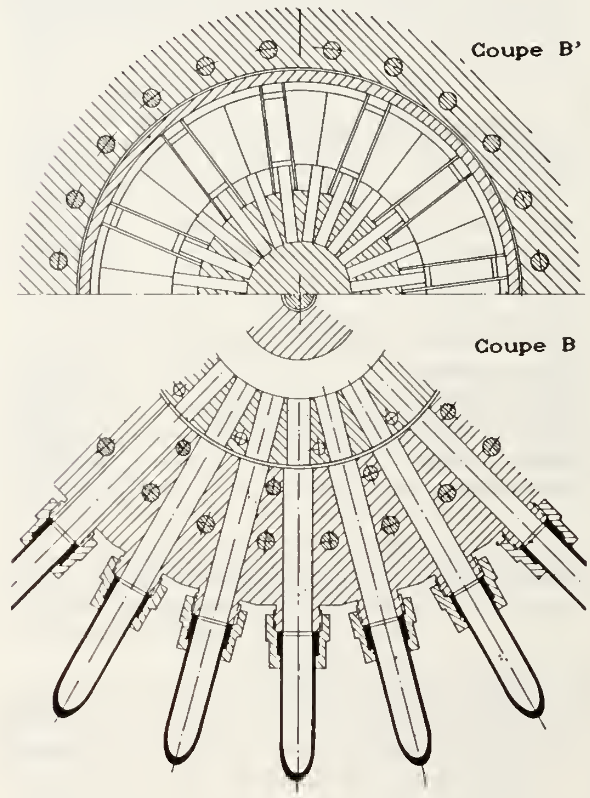

FIG. VI

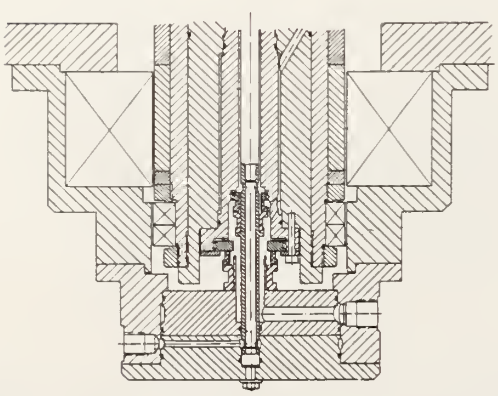

FIG. VII

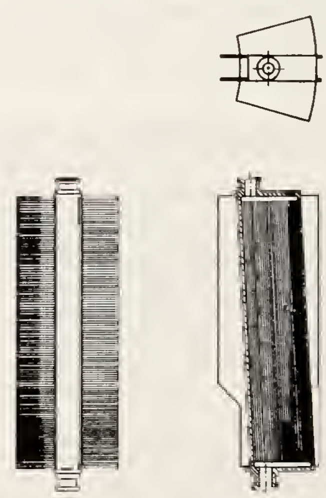

Fig. VIII

B4.4 Optimization of Stirling and Ericsson cycles by solar radiation

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SUMMARY

This paper considered a model consisting: (i) a source of radiation (the Sun) and (ii) two energy converters. The first converter (the absorber) transforms the solar radiation into heat while the second one (which is a Stirling or Ericsson engine) uses heat to produce mechanical work. Polarisation coefficients were introduced to characterize the radiation emitted by two components of the system (the Sun and the first converter). The maximum conversion efficiency of solar radiation into work was studied.

RESUME

Dans cet article l'auteur étudie un modèle qui est composé par (i) une source de radiation (le soleil) et (ii) deux convertisseurs énergétiques. Le premier convertisseur (l'absorbeur) produit de la chaleur à l'aide de l'énergie solaire et le second convertisseur (qui est un moteur Stirling ou Ericsson) utilise cette chaleur pour produire du travail. Des coefficients de polarisation ont été introduits pour caractériser la radiation émise par deux constituants du système (le soleil et le premier convertisseur). Le rendement maximal de la conversion de l'énergie solaire en travail a été étudié.

I. Introduction

As is well known, the higher the temperature provided by the working fluid from a solar collector, the lower will be the collector efficiency. However, for heat engines, the higher the energy supply temperature, the greater will be the efficiency. This incompatibility in temperature-efficiency relationships indicates that any solar collector-heat engine combination will have an optimum operating temperature. Many authors studied this optimum operating temperature and the maximum global efficiency of the collector-heat engine combination[1-9]. Almost all the quoted authors studied the ideal case of heat engines operating by Carnot cycles. Here we briefly refer to the more realistic case of the Stirling and Ericsson heat engines, which could be a solution for space power generation. This subject was previously approached by Howell and Bannerot[3] and some others authors within different theoretical frameworks[10-12]. Note that our approach is based on a development of the model proposed by Landsberg and Baruch[13].

II. Power generation and conversion efficiency

By following Landsberg and Baruch[13] here we consider a system consisting of two large reservoirs called pump (p) and sink (s) together with two converters. The first (RH) converter (the absorber) interacts with both the pump and the sink by interchange of isotropic radiation. In the RH converter the energy of the black-body radiation from the pump of temperature T_p is transfered to the second (HW) converter (the heat engine) where it is partially transformed into work.

When the sink is not a radiative media the balance equations for the energy and entropy received per unit area by the converter RH are :

$$\phi_{pc} - \phi_{cs} - \phi_{cp} - \dot{Q}' = 0 \qquad (1)$$

$$\psi_{pc} - \psi_{cs} - \psi_{cp} - \dot{Q}'/T_c + \dot{S}_g^{RH} = 0 \qquad (2)$$

where $\dot{S}_g^{RH}$ is the entropy generation per unit area of the converter RH. In case of the HW converter similar balance equations may be written :

$$\dot{Q}' - \dot{Q} - \dot{W} = 0 \qquad (3)$$

$$\dot{Q}'/T_c - \dot{Q}/T_s + \dot{S}_g^{HW} = 0 \qquad (4)$$

In (1-4) T_s and T_c are the ambient and converter temperatures while ϕ and ψ refer to energy and entropy fluxes, respectively. The suffix pc denotes fluxes from the pump to the converter RH and cs fluxes from the converter RH to the sink. Also, we considered the return flux from converter RH to the pump (cp).

The converter RH supplies the heat flux $\dot{Q}'$ to the converter HW. This heat flux is accompanied by the entropy flux $\dot{Q}'/T_c$. $\dot{S}_g^{HW}$ is the entropy-generation rate during work production while the rate of work and the heat flux transfered from converter HW to the sink were be denoted by $\dot{W}$ and $\dot{Q}$, respectively.
By a simple prelucration of the equations (1-4) we may determine the work rate $\dot{W}$:

$$\dot{W} = \phi_{pc} - T_s\,\psi_{pc} - (\phi_{cs} - T_s\,\psi_{cs}) - (\phi_{cp} - T_s\,\psi_{cp}) - T_s(\dot{S}_g^{RH} + \dot{S}_g^{HW}) \tag{5}$$

When isotropic black-body radiation is considered, the total emitted fluxes by component i towards component j (i,j = =p,c,s) are given by [13]:

$$\phi_{ij} = \frac{\sigma}{\pi}\frac{l_i}{2} B_{ij}\, T_i^4 \tag{6}$$

$$\psi_{ij} = \frac{4}{3}\frac{\sigma}{\pi}\frac{l_i}{2} B_{ij}\, T_i^3 \tag{7}$$

where σ is Stefan-Boltzmann's constant, l_i =1 or 2 is a polarisation factor for polarised and unpolarised radiation, respectively, and B_{ij} are geometric factors given by

$$B_{ij} = \int_{\Omega_{ij}} \cos\theta_i \, d\,\Omega_{ij} \tag{8}$$

In (8) θ_i is the angle between the radiation direction and the normal at the surface of component i while Ω_{ij} is the solid angle subtended by component j when viewed from component i. We denote by B_T the value of the equation (8) computed for the total solid angle accesible to the converter RH. The following relations apply[13]

$$B_T = B_{cp} + B_{cs} \tag{9}$$

$$B_{ck} = B_{kc} \qquad k = s,p \tag{10}$$

We developed the model of Landsberg and Baruch [13] to cover the case when the radiation emitted by the component i (i=p,c) is partially polarised. The flux ϕ_i may be decomposed into a flux ϕ_i^{pol} of polarised radiation (l_i=1) and a flux ϕ_i^{unpol} of unpolarised radiation (l_i =2) (Ref. 14, p.163). We define a polarisation coefficient $P_i \in (0,1)$ so that :

$$\phi_i = P_i\,\phi_i^{pol} + (1-P_i)\,\phi_i^{unpol} \qquad i = p,c \tag{11}$$

When P_i = 1 the radiation emitted is completely polarised while P_i = 0 corresponds to a source of unpolarised radiation. By using (6) and (11) we obtain the energy fluxes of partially polarised radiation :

$$\phi_{ij} = \frac{\sigma}{\pi}\frac{2-P_i}{2} B_{ij}\, T_i^4 \qquad i,j=p,c \tag{12}$$

A similar procedure leads to entropy fluxes :

$$\psi_{ij} = \frac{4}{3}\frac{\sigma}{\pi}\frac{2-P_i}{2} B_{ij}\, T_i^3 \qquad i,j=p,c \tag{13}$$

We shall use the following notations[13] :

$$r^4 = B_{pc}/B_T \qquad 0 \leqslant r \leqslant 1 \tag{14}$$

and

$$a=T_s/P_p \quad b=T_c/T_p \qquad T_s \leqslant T_c \leqslant T_p \tag{15}$$

so that

$$0 \leqslant a \leqslant b \leqslant 1 \tag{16}$$

By replacing the equations (6),(7),(11) and (12) in (5) and using the equations (9),(10),(14) and (15) we obtain the work rate under the form :

$$\dot{W} = \frac{\sigma}{\pi}\frac{2-P_p}{2} B_T\, T_p^4 \left[(1-\tfrac{4}{3}a)r^4 - \frac{2-P_c}{2-P_p}(b^4 - \tfrac{4}{3}ab^3)\right] - T_s(\dot{S}_g^{RH} + \dot{S}_g^{HW}) \tag{17}$$

The efficiency of work production is best defined by [13]:

$$\eta = \dot{W}/\phi_{pc} \tag{18}$$

Use of (12),(17) and (18) yields :

$$\eta = 1 - \frac{4}{3}a - \frac{1}{r^4}\frac{2-P_c}{2-P_p}(b^4 - \tfrac{4}{3}ab^3) - \frac{2\pi T_s}{\sigma(2-P_p)B_T r^4 T_p^4}(\dot{S}_g^{RH} + \dot{S}_g^{HW}) \tag{19}$$

Regard the entropy generation as taking place in the converter RH. By replacing $\dot{Q}'$ from (1) in (2) and using the equations (12)-(15) we obtain :

$$\frac{2}{2-P_p}\frac{\pi}{\sigma B_T T_p^3}\dot{S}_g^{RH} = r^4\left(\frac{1}{b} - \frac{4}{3}\right) + \frac{1}{3}\frac{2-P_c}{2-P_p}b^3 \tag{20}$$

In order to determine the entropy generation in the HW converter (the heat engine) we introduce the efficiency η_{HW} defined by :

$$\eta_{HW} = \dot{W}/\dot{Q}' \tag{21}$$

From (3),(4) and (21) we obtain :

$$\dot{S}_g^{HW}/\dot{Q}' = (1-\eta_{HW})/T_s - 1/T_c \tag{22}$$

By replacing $\dot{Q}'$ from (1) in (22) we derive

$$\frac{2}{2-P_p}\frac{\pi}{\sigma B_T T_p^3}\dot{S}_g^{HW} = \left[\frac{1}{a}(1-\eta_{HW}) - \frac{1}{b}\right]\left(r^4 - \frac{2-P_c}{2-P_p}b^4\right) \tag{23}$$

The analysis performed by Landsberg and Baruch[13] do not took into account the entropy generation rate $\dot{S}_g^{HW}$. Indeed, these authors refered to the converter HW as a reversible acting Carnot engine. In this case η_{HW} = 1-a/b and from (23) we see that $\dot{S}_g^{HW}$ vanishes.
Finally, we make some remarks on the interesting case when pump, sink and RH

and HW converters are in equilibrium. Then the three T_i become one and the same real temperature of black-body distributions. Consequently, $a_{HW}=b=1$ and $\eta_{HW}=0$. From (23) we obtain $\dot{S}_g^{HW}=0$ without other requirements. The equilibrium occurs also for the RH converter only when $\dot{S}_g^{RH}=0$. From (2o) we obtain a condition which must be fulfiled

$$r^4 = \frac{2-P_c}{2-P_p} \qquad (2o')$$

When a hemispherical pump is considered ($r^4=1$) the equilibrium occurs only when $P_c=P_p$.

III. Results and discussions

For a HW converter (the heat engine) operating on an air-standard Stirling cycle, the efficiency η_{HW} can be put in the form :

$$\eta_{HW} = \frac{1-T_s/T_c}{1+x(1-T_s/T_c)} = \frac{b-a}{b+x(b-a)} \qquad (24)$$

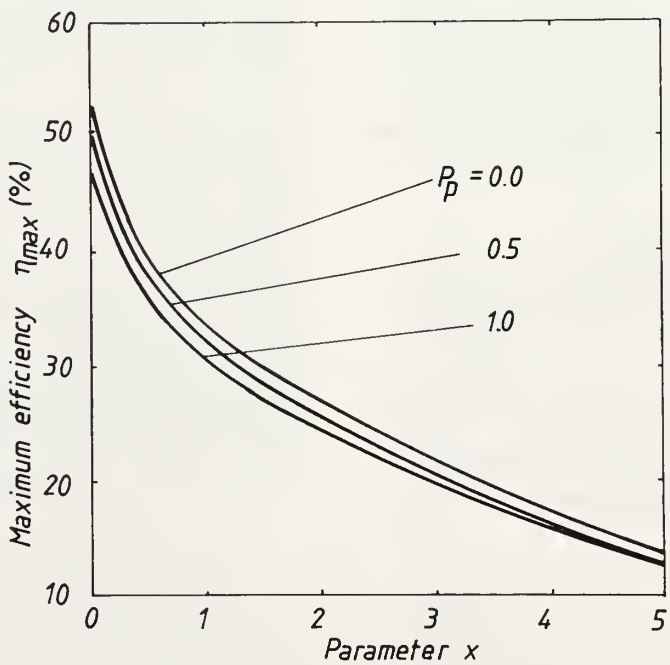

Figure 1 - The dependence of the maximum conversion efficiency η_{max} on the parameter x (equations (25) and (26)) for different values of the polarisation coefficient P_p. For details see the text.

where :

$$x = \frac{d\, c_v}{R \ln(v_1/v_2)} \qquad (25)$$

and d is the fractional deviation from ideal regeneration, R is the gas constant, c_v is the heat capacity at constant volume of the working fluid and v_1 and v_2 are the specific volumes of the constant volume regeneration processes of the cycle (v_1/v_2 is the overall compression ratio). Note that d=0 in (25) means ideal regeneration and η_{HW} reduces to the Carnot engine efficiency.

For the Ericsson cycle, the efficiency η_{HW} is also given by the equation (24) but x has the following form :

$$x = \frac{d\, c_p}{R \ln(p_1/p_2)} \qquad (26)$$

where c_p is the heat capacity at constant pressure of the working fluid, p_1 and p_2 are the pressures of the two isobaric regeneration processes and the other symbols are defined as before (for further details on the Stirling and Ericsson cycles see Ref.3).

In order to determine η we must evaluate the work rate $\dot{W}$, which can be computed by replacing (1) and (24) in (21) :

$$\frac{2}{2-P_p}\,\frac{\pi}{\sigma B_T T_p^4}\,\dot{W} = \frac{b-a}{b+x(b-a)}\left(r^4 - \frac{2-P_c}{2-P_p}\, b^4\right) \qquad (27)$$

The conversion efficiency is given now by (18),(12) and (27). To maximize η with respect to $b(=T_c/T_p)$ implies to solve the equation $d\eta/db=0$, i.e.:

$$b^5 - \frac{a}{4}\,\frac{8x+3}{1+x}\, b^4 + a^3\frac{x}{1+x}\, b^3 + \frac{a^2(x-1)-az}{4(1+x)} = 0 \qquad (28)$$

where the parameter z is given by :

$$z = \frac{2-P_p}{2-P_c}\, r^4 \qquad (29)$$

Figure 1 shows the dependence of the maximum conversion efficiency η_{max} on the parameter x for different values of the polarisation coefficient P_p, assuming $B_T=2\pi$, $a=T_s/T_p= 300/6000=0.05$ and $r^4= 2.17\times10^{-3}$ (this last value corresponds to a pump which subtend a solid angle covered by 100 Suns, i.e. concentrated solar radiation with a concentration ratio C=100). We considered the radiation emitted by the converter is non-polarised ($P_c=0$). As we see, the influence of the parameter x is important. The dependence of η_{max} on P_p is quite significant, especially at lower values of x. Detailed numerical results and discussions will be published in a future paper.

IV. Conclusions

The polarisation coefficients P_p and P_c of the black-body radiation emitted by pump and RH converter, respectively, has influence on the entropy generation in both converters RH and HW (the absorber and the heat engine). When thermal equilibrium is considered, the coefficients of polarisation are not independent.
The maximum efficiency η_{max} of converter RH-heat engine (converter HW) combination has a strongly dependence on the parameter x which characterizes the Stirling or Ericsson cycles (equations (25) and (26)). The dependence of η_{max} on the pump radiation polarisation is quite significant, especially at lower values of x.

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B5.1 Five axes magnetic bearings turboalternator

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1. INTRODUCTION :

The future needs for higher space power could be covered in the near future by solar thermodynamic or nuclear thermodynamic conversion. In both cases, the turboalternator is one of the preferred choices. The very high dependability and lifetime call for very reliable and flexible solutions. Up to now, gas dynamic bearings are generally used for the turboalternator demonstrators. It is shown that the magnetic bearings offer more degrees of freedom for the design and can cope with several operating modes forbidden to gas dynamic bearings.

2. THERMODYNAMIC CONVERSION :

The thermodynamic conversion can use three different cycles :
- Brayton,
- Rankine,
- Stirling (free pistons).

Brayton is generally preferred ; the table 2.1 summarizes the advantages and drawbacks of each cycle (from a space use point of view). The reading of this table helps to understand why the Brayton cycle is generally preferred despite its lower thermodynamic efficiency.

Table 2.1

Thermodynamic cycles comparison

Cycle	Brayton	Rankine	Stirling (free pistons)
Thermo-dynamic effi-ciency	medium	higher	highest
Turbine erosion	low	high risk	n.a.
Vibra-tions	low	low	high
Weight	low	low	high

3. TURBOALTERNATOR REQUIREMENTS :

The requirements for space use are slightly different from the ones for ground facilities.

The table 3.1. compares the most important requirements for space and ground use.

Space use put an heavy accent on reliability, lack of vibrations, lack of torque disturbance (during start up and normal operation in order not to disturb attitude control and hermeticity.

The efficiency is less important than a high radiator temperature which allows for a relatively small radiator surface.

One of the most difficult questions for the space turboalternator is the starting transient. The use of gas hydrodynamic bearings call for relatively short transients in order to avoid wear : this induces fairly high inertial torques which shall be countered by the spacecraft attitude control system, even if counter rotating alternators are used. This could be avoided by using magnetic bearings which can tolerate any speed and idle at low speeds.

One possible starting procedure with magnetic bearings is to accelerate the rotor using the alternator as a motor with essentially no gas flow. The speed up can be controlled by the attitude control system, thus avoiding any adverse interaction. When the nominal speed is reached, the gas (or steam for a Rankine cycle) is progressively admitted in the turbine and the alternator excited to maintain speed constant.

Table 3.1.

Space / ground requirements ranking

Space	**Ground**
Reliability	Efficiency
Low weight	Ease of maintenance
Hermeticity	Constant speed
High radiator temperature	
Lack of vibrations	
Limited starting torque	
Early failure detection	

4. MAGNETIC BEARINGS :

Definition :

The aim of any bearings system is to maintain the position of a rotating shaft against various loads. A shaft is defined by six degrees of freedom, where five must be controlled by the bearings. Two radial bearings are preventing two translations in two orthogonal planes and two tilting motions. A thrust bearing prevents axial displacement. The rotation of the shaft around its axis (its sixth degree of freedom) is controlled by the torque of the motor/generator.

Five axes magnetic bearings are using only electromagnetic forces to suspend the rotor. Those forces are balanced in five different directions. Pairs of opposite electromagnets are mostly used (figure 4.1). They are driven by current generators. The rotor position on an axis results from the balance between two opposite attraction forces.

Due to the nature of the field of the electromagnets, the rotor position on the axis is not stable without a feedback control. Therefore a sensor system is necessary to locate exactly the rotor on the axis. Induction sensors are mostly used. One of the feedback control characteristics is the electronic gain, which allows to have a stiffness equivalent to that one of a mechanical bearing.

Table 4.1
Principle of active magnetic bearings

Force	Position	Stiffness
Electromagnetic attraction (electromagnets + current generator)	Sensor	Electronic gain

Design :
The design of an active magnetic bearings system generally consists in the components described in Table 4.2.

Important design data are related to the dimensions :

- Speed / diameter
  The rotor must be laminated at the location of the electromagnets and the sensors, in order to reduce the electromagnetic losses (eddy current and hysteresis) to a minimum. The strength of the laminations material is the actual limit of the rotor peripheral speed (200 m/s for FeSi laminations). Thus, the maximal rotation speed of the rotor is directly linked to its diameter at the radial magnetic bearing air gap.

- Air gap
  The air gap of an active magnetic bearing can be adapted to the application (from less than .4 mm to over 1 mm). In any case, it is larger than for other bearings. This unique feature brings various possibilities of rotor displacement within the air gap. It also allows to protect the bearings with an auxiliary mechanical bearing (half air gap).

Table 4.2
Typical components of
5 axes magnetic bearings

	Force	Position	Stiffness
Radial bearing nb 1	2 pairs of electromagnets 4power amplifiers	2 sensor systems	2 control loops
Radial bearing nb 2	2 pairs of electromagnets 4power amplifiers	2 sensor systems	2 control loops
Thrust bearing	1 pair of annular electromagnets 2power amplifiers	1 sensor	1 control loop
Mechanical safety device	auxiliary bearing radial/axial (generally dry lubricated ball bearings)		

A radial bearing, a thrust bearing and a set of auxiliary bearings are depicted on figure 4.2.

The power amplifiers and the control loops are placed in a control cabinet for ground applications (which may be remote) linked by cables to the machine and in a low volume electronics box for space applications. The control cabinet includes power supply and interface functions. Monitoring is possible.

Characteristics of five axes magnetic bearings :

All positions : upwards, downwards, any position is allowed with five axes magnetic bearings (this is not possible with 4.5 axes control, where the weight of the rotor is not counterbalanced by an electromagnetic force in one direction).

Load capacity : is independent of speed. As soon as the bearings are switched on, the levitation occurs, allowing the rotation to be started (the only limit to the load capacity is the induction surface of the electromagnets).

Speed : active magnetic bearings can be used at very high speed (only limited by the rotor materials) but also at any lower speed. Idle is not a problem.

Lifetime : none of the parts described in table 4.2 will sustain permanent friction. Thus, mechanical wear is avoided. the lifetime of mechanical parts is virtually infinite.

Reliability : thanks to the large air gap (compared to gas bearings) auxiliary bearings are added. They would cope with transient failures of the magnetic bearings (overload, control failure) which could happen.

Safety : thanks to the monitoring possibility given by the control cabinet, early failure detection may be performed at the machine level (changes in : rotor displacement, bearing loads, vibrations, ... are detected).

Temperature : wide range is allowed with magnetic bearings, from cryogenic temperature (no lubricant) to above 400°C (with special insulation).

Vacuum : operation in vacuum is not a problem with magnetic bearings as no lubricant, no air cushion is needed.

Vibration free : a special electronic function of five axes magnetic bearings allow the shaft to rotate around its inertial axis. Thus, unbalance no longer creates forces.

Crossing of critical speed : the electronic control of an active magnetic bearing may be used as damper. The frequency may be chosen.

Shaft axial position : thanks to a large air gap at the electromagnets (point A) and to a sensor located in a "strategic" position (point B), which not the electromagnets but, for example, the wheel of a turbomachine, the shaft axial position is fixed on point B. The thermal expansion of the shaft occurs around point A (figure 4.3).

Applications :

The five axes magnetic bearings have been used in a number of demanding applications since years.

On ground, they are used for applications where reliability is a premium, e.g. natural gas compressors in remote locations,

or for applications where conventional lubrication or bearings use are not possible :

- high vacuum turbomolecular pumps,
- cryogenic expanders,
- loaded fuels (crude oil pump),
- high speed machining heads,

or for applications where precision is a premium :

- earth ressource image generator,
- optical surfaces direct machining.

For space applications, they have already received a large application. The first application was a magnetic bearing momentum wheel for geostationary spacecraft using fully redundant bearings and electronics.

Another one was the turbomolecular pump for SPACELAB, Turbovac 100 MSL.

These early products were not incorporating the latest improvements in electronics, like the autobalancing function and the PWM amplifiers. These two techniques - already well proven on ground - will help to enhance the interest of five axes magnetic bearings. The autobalancing function helps to fulfil absolutely the microgravity requirements, the PWM allows a huge improvement in efficiency and size of the electronics.

5. TURBOALTERNATOR DESIGN :

Turboalternator design inputs :

The main points to consider in any design (gas or magnetic bearings) are :

- turbine to alternator thermal discoupling,
- alternator cooling,
- shaft critical frequencies,
- rotor unbalance,
- redundancies,
- allowed emergency operations.

The turbine to alternator thermal discoupling could be obtained by using a thin section hollow shaft (rotor) and superinsulation on the stator. In addition, a small quantity of the compressor flow can be diverted to cool these structures.

The alternator (and magnetic bearings) cooling can be performed by the working gas itself or by the cooling loop of the station. The use of the working gas is simpler but this gas may be rather hot (100°C), thus potentially impairing life and efficiency ; the use of cooling loop offer the potential to work close to ambiant temperature but may lead to complicated configurations (rotary joints). For larger facilities, a very good compromise is to use the Brayton cycle working gas in an auxiliary loop including a refrigerator to cool very efficiently the alternator. The use of cryogenic alternator is possible only with magnetic bearings.

Rotor unbalance :

The rotor unbalance is a source of vibrations. The unbalance can vary with time, especially if the turbine undergo erosion (Rankine cycle with saturated vapour) ; the use of magnetic bearings allow to cancel the unbalance, by virtue of the self balancing function, and to adapt the control law to the unbalance shift.

Redundancies :

The magnetic bearing electronics presents a rather high part count, for this reason, the question of electronics redundancy could be raised. This could be provided by active or cold redundant circuits. The bearings themselve can be redundant but this generates a loss of useful space. The bearings failure is a very unlikely event. In any case, conventional emergency bearings (generally dry lubricated roller bearings) are provided.

The mains supply failure can be prevented by using the alternator, or a part of it, as a backup generator. Therefore, no battery are needed to provide supply backup.

Allowed emergency operations :

If for some reason, an emergency stop of the turboalternator is required, this could be obtained very simply (in the case of magnetic bearings) by switching off the turbine inlet valve and dissipate the rotor energy by using the full power of alternator in an external load. The big interest of this operating mode is that there is no requirement to maintain a gas flow or gas pressure to supply gas bearings.

30 kW range design :

The 30 kW range turboalternators are to be used in the next generation Space Stations (e.g. EMSI). They are primarily intended to be simple and reliable.

The conventional design with gas bearings (Figure 5.1) uses an alternator located between bearings, the turbine and compressor being mounted at the shaft extremities.

The use of magnetic bearings allows more freedom in the design. One of the possible designs involves the use of an alternator rotor mounted at the shaft extremity with axial bearing, while turbine and compressor are mounted between radial bearings or else compressor between bearings and turbine at shaft extremity (Figure 5.2). The turbine housing can receive a sensor to detect rotor position and control the axial bearing to minimize the play and increase the turbine efficiency.

1 MW range :

This range is intended to be used on beamed power demonstrators. The use of larger hardware allows for more elaborate construction.

For example, a cryogenic alternator could be used, this enables to enhance the alternator efficiency, possibly to use a superconducting inductor (especially if high temperature superconductors make progress in the mean time) thus leading to the use of an ironless rotor, with much lower inertia and higher critical frequency than a conventional rotor.

Such a size allows also the use of multistage turbine and compressor, the possible shaft oscillations induced by the increased length can be cancelled by using a third radial bearing acting as a damper.

6. CONCLUSION :

The use of five axes magnetic bearings on future turboalternators for space use will offer numerous advantages. Their life is nearly indefinite, the microgravity and attitude control disturbances are nil, the design flexibility allowed by the magnetic bearings offer opportunities like cryogenic alternator.

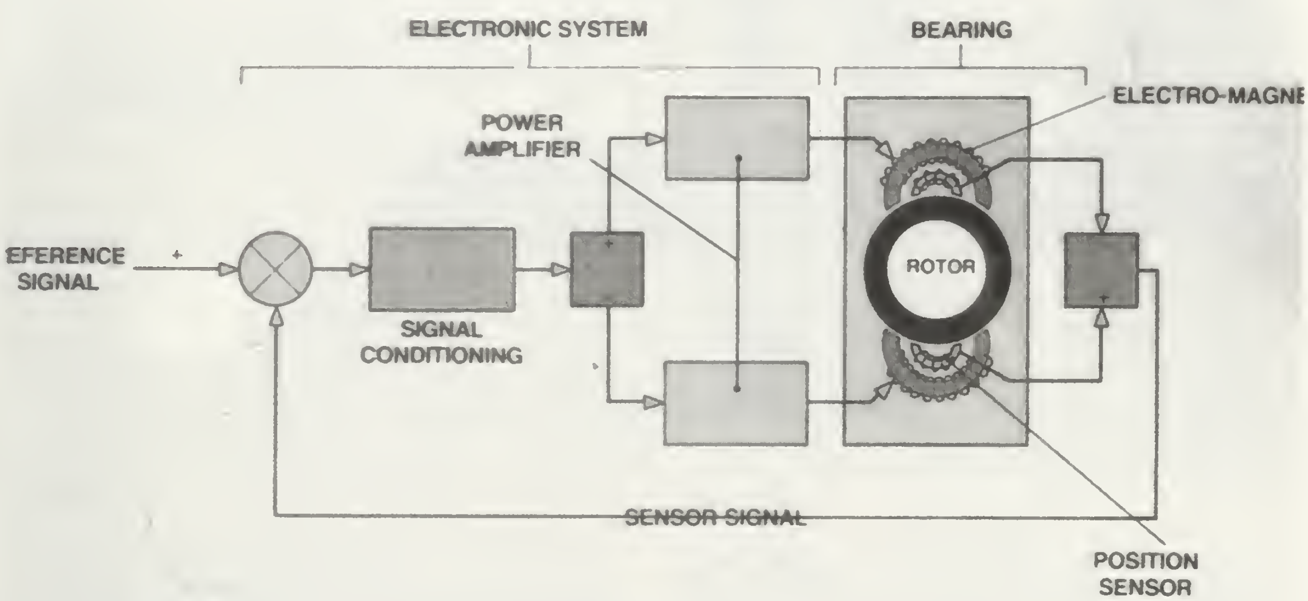

FIGURE 4.1

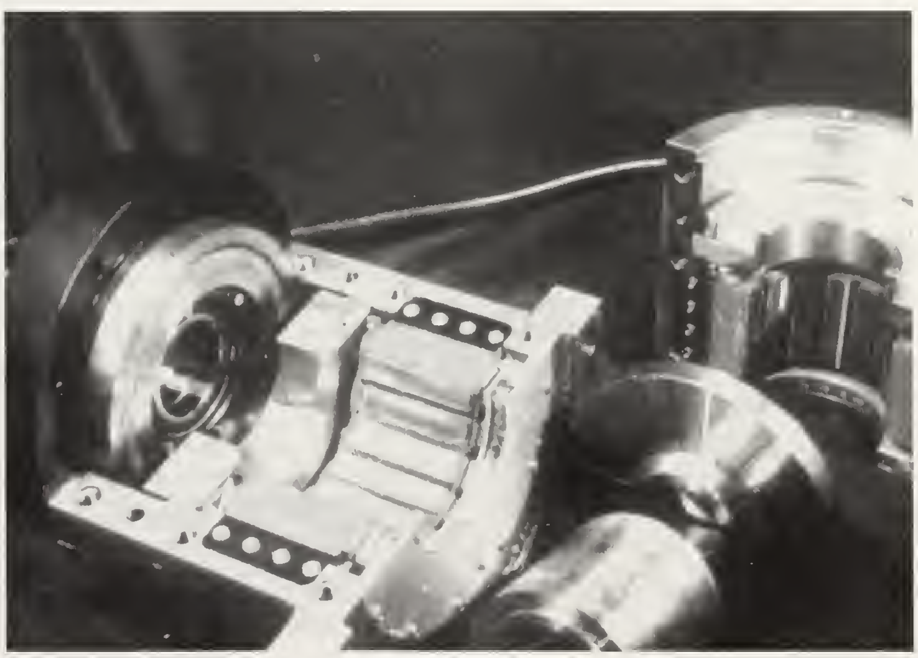

FIGURE 4.2

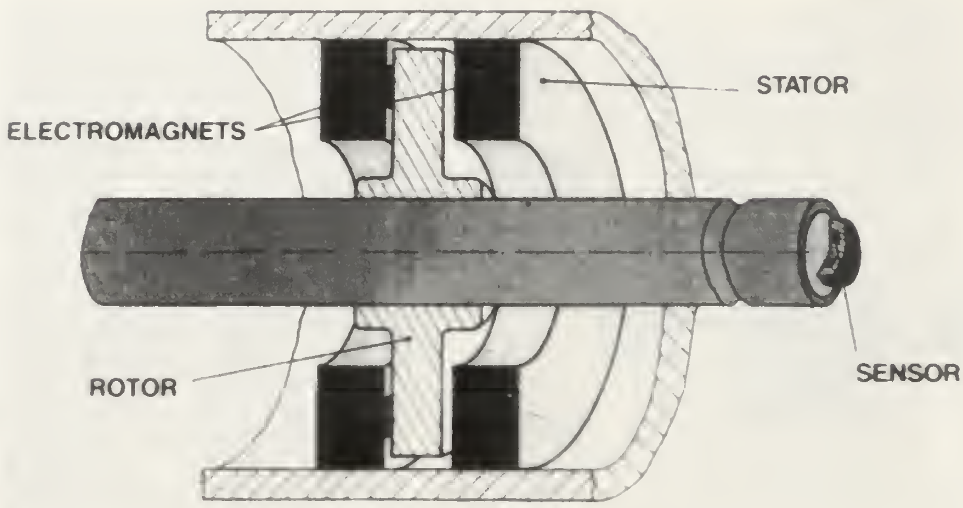

FIGURE 4.3

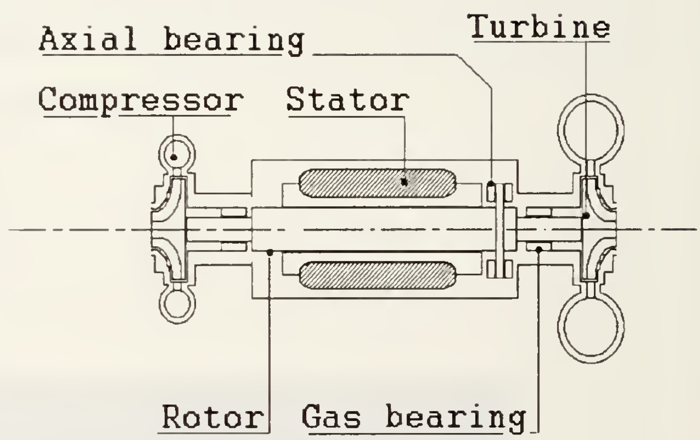

FIGURE 5.1

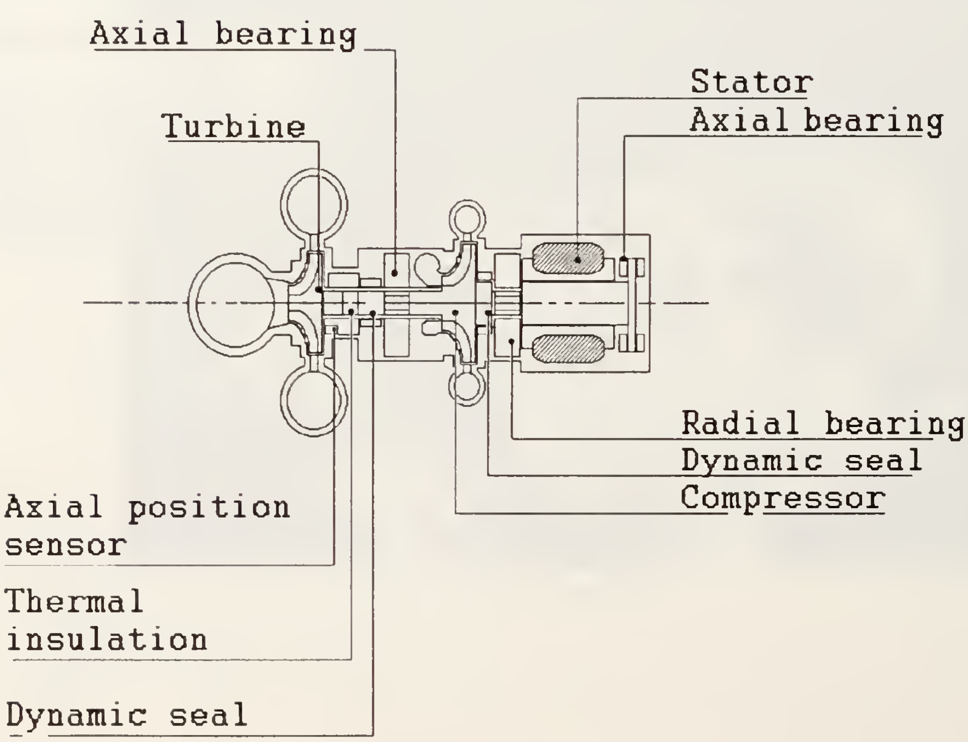

FIGURE 5.2

B5.2 Developing space power Brayton system with solar heat input - Research of working process of high temperature latent heat storage system

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ABSTACT

In this paper are presented the results of preliminary development on the dynamic solar power system suitable for space application. From the results of development, two schemes that satisfied most demands have been chosen.

This paper also describes the results of experimental investigation on the heat transfer in phase change material (PCM) that would be used in one of the key elements such as thermal energy storage (TES) that is integrated receiver of solar flux.

RESUME

Dans ce travail sont présentés les résultats d'un développement de l'installation solaire dynamique énergétique, pour l'utilisation spatiale. Comme résultat de cette élaboration ont été choisis deux schémas qui satisfaisaient les spécifications. Dans ce travail sont aussi décrits les résultats d'une recherche expérimentale du transfert de la chaleur dans des matériaux à changement de phase (MCP). Il est possible d'utiliser ce matériau dans un élément principal comme le récepteur thermique intégrant un accumulateur thermique.

Introduction.

This Study has been conducted in Dniepropetrovsk State University to generate and evaluate advanced solar dynamic Brayton engine cycle on the 3-5 kWt size range. Solar dynamic systems represent a great potential for space power generation. These systems offer the advantages of safe, nondegretable power production as compared with other space energy systems.

The system and component design concept are presented along with results of first-order trade-off of the effects of major system design parametrs on system electric power output. All technical performance of such system are presented in following table 1.

Table 1.

Useful electrical power		3-5kWt
Eclipse time		35 min
Duration orbiting time amount		100 min
Maximal total mass of whole system		400 kg
Size of system at transportable state		
length	no more	3,3m
diameter of concentrator	no more	1.5m
Life time without technical service		5 year
System power efficiency		0.312
Conversion system efficiency		0.367
Working medium		mixture Xe+He
Molecular mass of working medium		
Mass flow rate		0.2 kg/sec
Temperature of working medium:		
-inlet of receiver-heat storage unit;		909.6K
-outlet of receiver-heat storage unit.		1103K
Pressure of working medium :		
-inlet of receiver-heat storage unit;		0.1784MPa
-outlet of receiver-heat storage unit.		0.1750MPa

Common analysis.

To carry out this demands during preliminary study are analyzed 8 different models of power systems. All of of there are presented in figure
1-with paraboloid reflector and plate and cross formed radiator;
2-with paraboloid reflector and cylindrical radiator;
3-with paraboloid reflector and divided heat receiver and heat storage system;
4-with paraboloid reflector fulfilled as Kassegrain type collector and tube ray radiator;
5-with facet reflector and tube arrayed radiator;
6-with annular paraboloid reflector and cylindrical radiator;
7-with parabolocylindrical reflector and tube arrayed radiator;
8-with parabolocylindrical reflector and cylindrical radiator.

In this schemes all paraboloid reflectors could be deploy in external size.

Individual analysis.

As results of different causes all schemes are rejected except schemes having number 3 and 4.
More in detail scheme 3 are presented in figure 2, where:
1-tube arrayed network of radiator;
2-collector tube of rotating unit and radiator;
3-wheel of radial flow compressor;
4-recuperator;
5-alternator rotor;
6-alternator stator;
7-gas bearing;
8-wheel of radial flow turbine;
9-heat storage system;
10-aperture window;
11-heat receiver structure;
12-heat receiver;
13-framework of power station;
14-central reflector of radiator;
15 deployable petal form part of reflector.

Mounting devices of reflector allow it transference relating framework in radial direction. Useful surface of reflector are
coupled with surface of central paraboloid reflector and deployable petal form part of reflector.

The rotating unit included the radial outflow compressor, radial inflow turbine and alternator rotor. The compressor and turbine are mounted on the common shaft at console type relatively alternator. The rotating unit is supported by gas journal. Recuperator are fulfilled as annular cylinder placed around rotating unit. It is a gas-to-gas plate and fin pure counter flow heat exchanger. Recuperator design illustrated in figure 4.

This design permit to avoid using of long tubes.
The radiator are fulfilled in radial arrayed tube framework and represent rigid construction produced by welding. The heat receiver are coupled with thermal energy storage.(TES) In this device the collected colar energy is directly transferred to the integral thermal energy storage of receiver and the thermal energy is then extracted by working fluid that passed through inner volume with ball shape capsule filled in by heat storage medium. The incident solar flux penetrate in receiver through the glass window. The working fluid transported the extracted heat energy to the power system. TES are placed in central cone form body among heat receiver. The inner volume of TES are divided by distance lattice.

Conclusion.

The deficiency of such system are following:
-necessity to decrease the tangential part of outlet velocity to about zero value, that caused by design of plate and fin heat exchanger. As result of that was increasing pressure drop;
-the using of radial outflow turbine had been less efficiency than radial inflow turbine;
-complicated fabrication of hermetic junction between glass of window and metal of receiver at condition of high temperature.

Analysis of facet scheme.

It was also designed scheme in which instead monolithic paraboloid form mirror was used facet collector. Each facet are mounted with special devices on common frame and attitude separately with respect main focus of whole system. For production of reflectivity surface it was chosen composite technology for producing refectory framework with following plotting in vacuum of aluminum and defense covering

All facets are rated on six type with focus length.

The package scheme with Kassegrain type collector is shown in figure 3. There are:
1. tube arrayed frame that reinforce the secondary mirror;
2. fin arrayed tube channel of radiator;
3. central mirror of collector;
4. petal form deployable panel of collector;
5. secondary mirror;
6. receiver with thermal storage system;
7. framework of power system;
8. recuperator;
9. rotating unit;

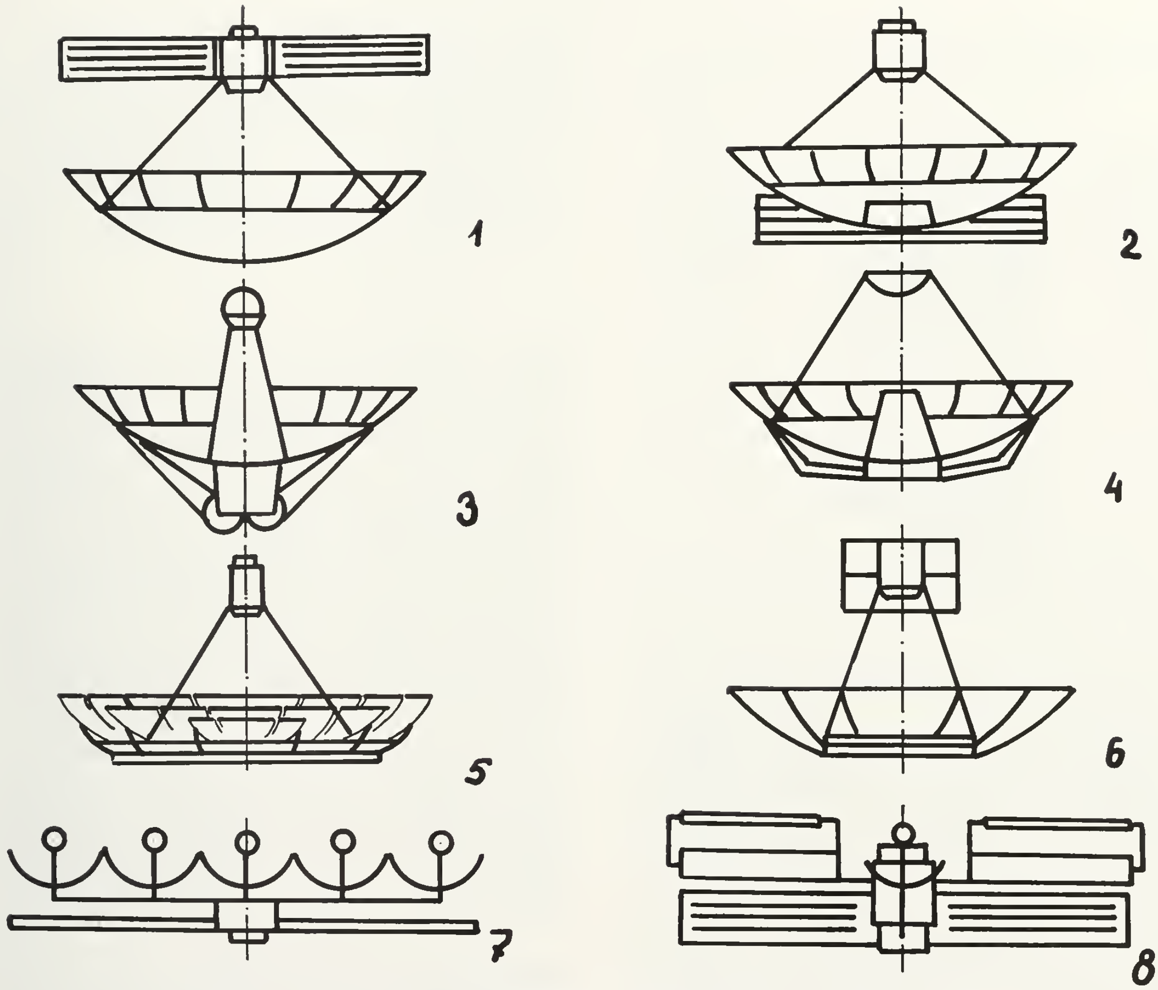

Figure 1. Concept schemes of spase power dynamic systems.

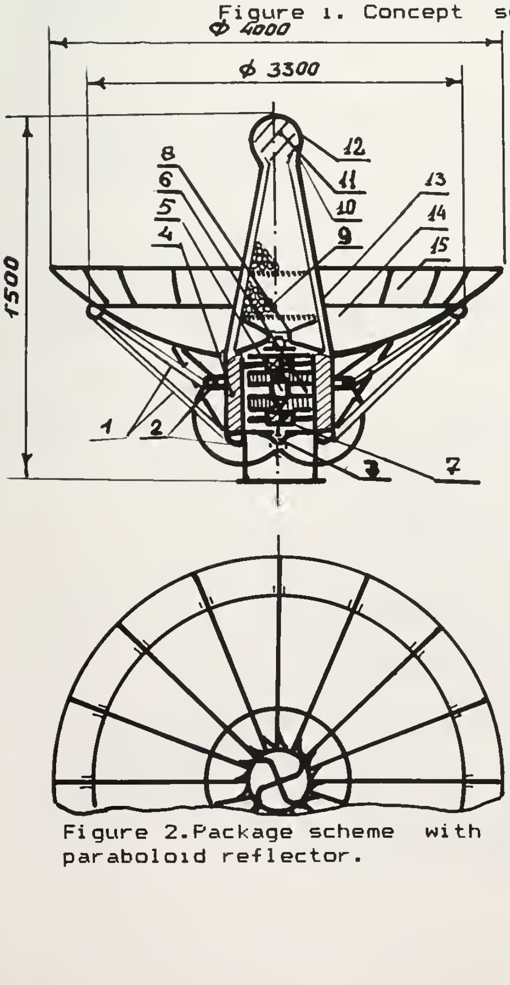

Figure 2. Package scheme with paraboloid reflector.

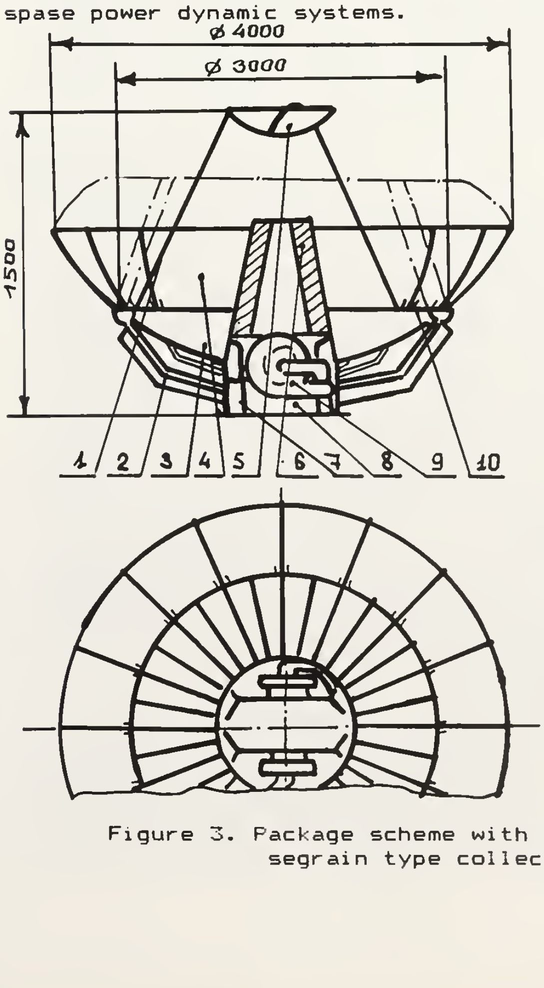

Figure 3. Package scheme with Kassegrain type collector.

10.the mounting device of petal form part of reflector;

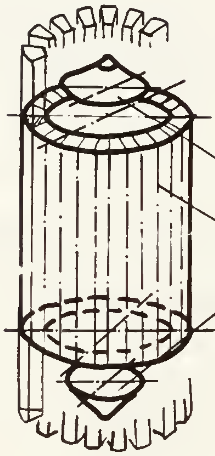

Figure 4. Recuperator design.

The central reflector in this scheme are similar at previous. The difference between them is only in the manner of producing central mirror. In the last case it made from three layer that rigidly connected with central part of framework of energy system.

The secondary mirror are mounted with three hollow rods. Two from theirs are used as duct for coolant that reject heat from secondary mirror. The working medium pass in sequence through the recuperator and spiral form duct situated on back side of mirror.

The hole heat receiver combined with thermal storage system was packaged in central part of energy setup. The peculiarity of such system is presence of add part of duct that directly receive solar energy up to inlet of combined receiver. Rotating assembly is made as one unit and consist from radial outflow compressor and radial inflow turbine.

Analysis.

The positive quality of such system are following:
-convenienceof package the heat receiver with high performance;
-good package of subsystem collector-receiver as it was take place in previous scheme;
-Brayton power system with Kasegrain type collector better satisfy the imposed limit in maximal dimension.

But there are following deficiency in this scheme:
-presence of secondary mirror decrease the reflector efficiency of collector;
-there are more value of pressure drop as result of need cooling the secondary mirror.

As result of trade-off the scheme with Kassegrain type collector are more preferable. The mirrors with short focus length meet the demand of limit size. Use of hole receiver combined with thermal energy storage decrease heat loses. There are no need of deploy of system for majority of units except petal form part of collector. There other units are tightly connected.

The mounting common package and its attenuation would be fulfilled in plant condition on Earth.

Part 2. Research of working process in high temperature storage system.

In this paper also described the results of development of the latent heat storage systems in aforementioned dynamic spase systems. The heat storage system in its is combined with heat receiver. The maximal temperature in this system would be approximately in range 1150-1175K. Fluoride lithium (LiF) would be used as phase change medium (PCM).The main peculiarity of this PCM is its transparentness.

One of the main problem erasing during developing such systems is low heat transfer rate in thermal energy storage (TES) as result of low heat conductivity of PCM. For solving this problem are proposed devices, that enhanced heat transfer rate.
The purpose of this investigation was to obtain an improved understanding of working process which occur during the melting of a semitransparent materials at high temperature. The experiment was performed with cylindrical heat storage enclosure. The cross section of this enclosure was shown in figure 5.

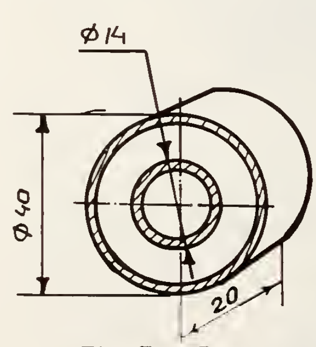

Fig 5. Cross section of heat storage capsule with PCM.

The size dimension of heat storage capsule and weight of PCM in it are presented in table 2.

Table 2

Outer diameter	40 mm
Area of external surface	52.24 cm
Inner diameter	12 mm
Wall thickness	1 mm
PCM mass	24.88 g
Capsule height	20 mm
Capsule mass	74.12 g

The test apparatus was consist from isolated cylinder form volume with length Ø,45m and inner diameter Ø.18m. Inside this volume was installed 5 lamps with wolfram filament. Electrical power for each lamp was 1 kWt.With special switch it was possible to use any number of lamp. By visual observation it could be research the distribution of liquid and solid phase during melting-freezing cycles. The empty volume with gas and volume with solid PCM during freezing proses had more dark color relatively volume of capsule. Measurement of surface temperature was arranged with chromel- alumel thermocouples placed circumferentially on outer and inner surface of capsule. Before experiment each capsule was was filled in special device with liquid PCM and after freezing was sealed also in special device by welding under argon atmosfier.The properties of PCM and capsule material are presented in table 3.

Table 3.

Material	wt m gr	kg m	J g	K	
LiFl	5	1815	1050	1123	2000
LiFs	4	2295			2000
X18N9T	27	7900			502

The average heat losses are evaluated at every level of capsule temperature with using experimental dates at cooling velocity with according correlation:

Q=(Mc*Cc+Mpcm*Cpcm)_ ;

where Mc,Mpcm-mass of capsule and PCM; Cc,Cpcm-specific heat capsule and PCM materials;

Q -cooling rate at switched off lamp condition. Its value measured experimentally.

Calculation result with according previous correlation for different temperature level are presented in figure 6.In there also presented the results surface heat flux calculated by dividing the average heat losses on capsule surface.

Analysis of dates presented in figure 6 showed that in case of existing radiant input only from one side capsule there taking place the uniformity of temperature fields circumferentially around capsule.

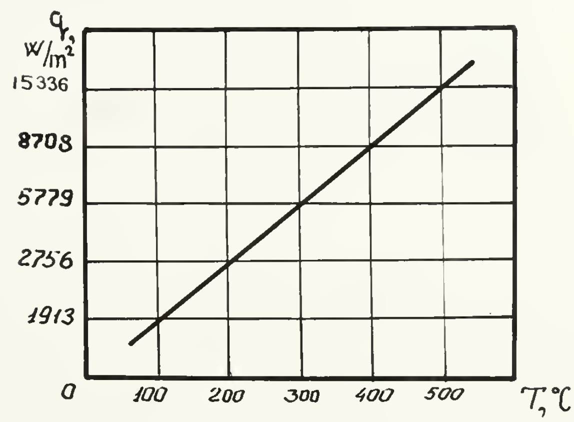

Figure 6. Overal heat loses as function of capsule temperture.

In this figure did not present dates at temperature above 900K as in that case there are exist heat affect of fusion proses of PCM on surface temperature.Temperature level presented in figure 6 was taken as mean value between thermocouple meanings installed at outer and inner capsule surface.As the same manner was calculated rate of heating.

In following run of experiments for deleting radiant flux input on top surface of capsule in experimental setup it was installed three capsules with measurement temperature fields at middle capsule.

This experiment was performed for evaluation capsule heat flux in radial direction and temperature gradient in this direction also. Temperature variation in this case are presented in figure 7 .

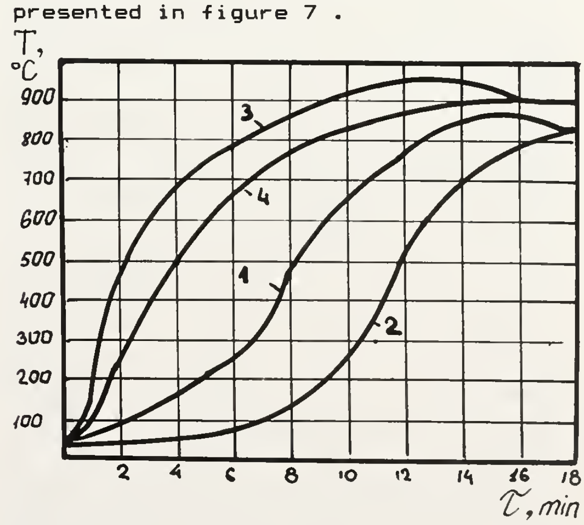

Figure 7. Temperature variation at outer (1,3) and inner (2,4) capsule surface during heating;
1, 2 -surfase temperature of single capsule;
3, 4-temperature of capsule with shield.

Analysis datmes presented in figure 7 showed that presence of shields lead
to increasing temperature gradient in capsule radial direction. Also it was noticed that the melting proses begin at 2-3 minutes latter.
It was fulfilled experiments with capsule heating when was switched on successively 1,2, 3, 4, 5 lamps. The results of heating rate at level temperature 600K are presented in table 4.
The results presented in table 4 testified assumption that in condition of our experiment exist addition of radiant flux from different lamps. Melting proses in capsule take place in condition, when was switched on only four or five lamps. Temperature time dependence at outer and inner capsule surfase about five lamp switch on are presented in figure 7 (curve 1, 2)

Table 4.

Number of switched on lamps	1	2	3	4	5
Heating rate J/sec	26,79	53,41	84,22	119,15	147,7

It was also fulfilled run of experiments in which heated the capsule fabricated from same material as aforementioned capsules but without hollow. The temperature variation ii this case are presented in figure 8. This dates revealed insignificant difference between temperature fields from external heating side and inner side of sapsule and presence difference at opposite side. Uniformity of tempertrature field in capsule with PCM was aproximately equal with its in the same form capsule fabricated entirely with steel. When PCM was frozen this difference in capsule with PCM was more then in continuous capsule. When PCM was melted this difference was smaller.

This dates testified that radiant heat transfer have major role in heat transfer with semitransparent materials.

It was fulfilled 20 melting cycles in capsules with PCM. Maximal temperature at outer surface was 1175K and 1160 at inner.

For the run experiment without shields a temperature difference was less at 5-10K. In both case these difference was less than in case with capsule fulfilled only from stainless steel.

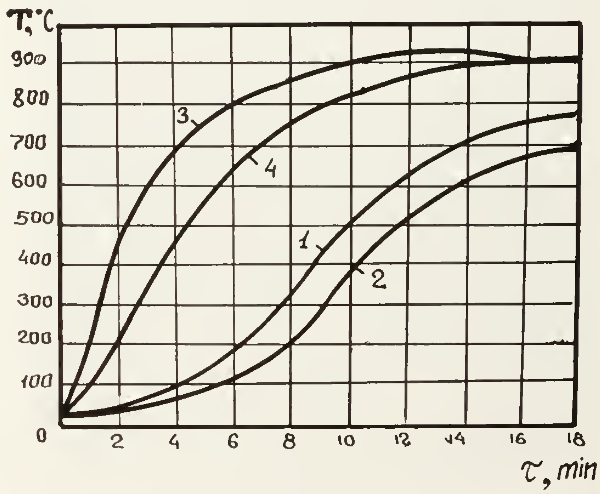

Figure 8. Temperature variation at outer (1,3) and inner(2,4) surface of capsule with PCM (1,2) and the capsule fabricated from stainless steel(3,4)

According with more dark color in top part of capsule during cooling it was concluded that liquid PCM collected in lower part of capsule. Presence of hollow volumes was connected with filling technology.
Analysis of temperature curves showed that during 90 percentage freezing time surface temperature changed in 1175-1125K range. It was 3,5 minute duration for each capsule.
Heat flow range in this case was 25000-36000 Wt/m.

B5.3 A high-temperature solar receiver for space power

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This paper will discuss a radiation receiver for concentrated solar energy which approaches the ideal receiver performance limit, providing very high working fluid temperatures for space energy conversion or propulsion. For thermal power cycles, high temperatures are clearly advantageous for high cycle efficiency and also allow higher heat rejection temperatures to reduce radiator weight. In propulsion applications higher temperatures lead to higher ISP values, resulting in lower propellent weight. Conventional approaches for using solar radiation for thermal power or propulsion systems employ cavity receivers in which radiation is absorbed on solid surfaces and transferred to the working fluid by conduction. Materials limitations usually restrict peak surface temperatures to the range 1500-2000 K, much below the theoretically achievable temperature of 4000 K for focused radiation from an ideal solar collector. Moreover, the reradiation losses from conventional receivers typically result in peak working fluid temperatures significantly below 1500 K. The flowing-gas radiation heater (FGRH) discussed in this paper eliminates these constraints by depositing focussed radiation directly in an absorbing fluid (working fluid) rather than transferring energy to the fluid by conduction through a solid absorber.

In the FGRH, radiation is directed into an absorption chamber containing an absorbing gas which flows in the direction of radiation propagation. Gas enters the chamber at a modest temperature and is heated as it absorbs solar radiation. Radiation emitted by the hotter gas in the interior of the chamber is absorbed by the cooler gas near the receiver entrance, which leads to significantly lower reradiation losses at a given gas exit temperature, than the losses incurred by a blackbody surface receiver heated to the same temperature. The receiver gas may be an appropriate working fluid for a power system (e.g. Brayton cycle), seeded with a small quantity of a gaseous species which efficiently absorbs sunlight. By tailoring the absorption/emission spectrum of the seedant, it is possible to enhance the trapping of reradiation (similar to the greenhouse effect) and approach the color temperature, rather than the intensity temperature of the incoming radiation.

Previous analyses have been carried out to determine the temperature profile and radiation losses from an FGRH using a one-dimensional model for radiative and convective heat transfer.[1-3] This work demonstrated that for gray gases the FGRH efficiency could be 25 % higher than the efficiency of a blackbody absorber at high solar fluxes. Gases having stronger absorption at long wavelengths result in even higher efficiencies. Alkali metal vapors were found to be suitable as seedants for working fluids such as He or H_2, owing to their strong, wideband absorption at high temperature. More recently, this work was extended to treat a more realistic 2-dimensional case, with a reactangular chamber geometry (for calculational simplicity), and including radiation transfer to the sidewalls of the chamber[4]. Although loss to the sidewalls reduces the receiver efficiency, it was found that gas temperatures exceeding 3000 K are possible under realistic conditions.

This paper will present results from the analysis of radiation transfer in a cyclindrical FGRH system. The model includes temperature-dependent spectra of seedants and viscous effects in the flow. The application of the FGRH in space power cycles will be discussed, with emphasis toward designs which optimize the power-to-mass ratio and minimize transport volume.

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SPS 91

B5.4 Solar dynamic power generation system

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It is considered useful to pursue the development of solar dynamic conversion in parallel with the development of advanced photovoltaic generators.

Work should be focused on the development of the critical system components, ie. the concentrator and receiver, and on the design of efficient heat exchangers, thermal machinery, and electric generators.

Early in the development program, detailed codes are needed for simulating the behaviour of the system and estimating its performance. These codes should provide direction to the program. A large number of experimental investigations will have to be performed on ground to test all the aspects of the systems, starting with technology verification activities at the subcomponent level. In particular, these activities should support the selection of the materials for the receiver and the concentrator.

The utility of early verification in space has been identified in the area of thermal energy storage : it concerns primarily the study of the formation of voids in the storage materials under microgravity conditions.

It does not seem possible at the present stage to define in detail all the successive steps of a development program having as a final goal the in-flight verification of a demonstrative module. The initial phase of such a program is proposed by Ansaldo, focusing on the definition of a Brayton reference module and including some experimental efforts on the storage materials.

B5.5 Multicomponent liquid-metal coolants with regulated properties for space nuclear reactor-generator of big orbital station

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SUMMARY

The method of experimental investigation of thermodynamic functions of multicomponent liquid-metal systems on the basis of alkali- and alkali-earth metals is proposed and realized. Being both low--temperature and high-temperature coolants simultaneously these systems can be used for solar and for nuclear power installations in space.

RESUME

La méthode d'étude expérimentale des fonctions thermodynamiques des systèmes multicomposants fluides métalliques sur la base des métaux alcalins et alcalino-terreux a été proposé et réalisé. Ces systèmes peuvent être utilisés dans des installations énergétiques solaires et nucléaires des stations orbitales, en représentant simultanément fluides caloporteurs des hautes et des basses températures.

1. Abstract

Named systems are the basis of the new kind of coolants and working fluids for energetics and technology. The method is based on calculation of characteristical functions (potentials) in broad area of temperatures and concentration by integration of differential equiations of chemical thermodynamics with experimental determination of:
1) underintegral functions (partial and integral enthalpies of formation in all area of named parameters of state) and
2) boundary conditions (concentration dependences of activities or Gibbs energies at one - not high - reference temperature $T_1 \approx 400$ K). The advantages of this algorythm which can be provided with reliable input experimental data input experimental data and permits to obtain inwardly-agreed thermodynamic description of studied systems are are demonstrated. For solution of both experimental tasks two groups of installations were constructed. The first group includes a complex of calorimetric apparatus with level of sensitivity permitting to determine of excessive thermodynamic functions of liquid-metal systems. The second group is based on determining of activities of components on partial pressure of saturated vapour obtained by measurement of inensivity of their atomic flows with help of effusion method using electroneam bombardment. The data for thermodynamic functions in diapason $0 \leqslant x_i \leqslant 1$, $200 \leqslant T \leqslant 1200 \div 1500$K are obtained. All the data at high and extremely low temperatures were absent in literature. Physical interpretation of results are submitted.

2. Nomenclature.

a	- thermodynamic activity
Cp	- heat capacity at constant pressure
G	- Gibbs energy (see Z)
H	- enthalpy (see Z)
N	- number of particles
S	- entropy (see Z)
$S_{cc}(O)$	- concentration correlation
x	- mole fraction
Z	- thermodynamic function in general, absolute value
ΔZ	- integral thermodynamic function of formation of alloy
$\Delta \bar{Z}_i$	- partial thermodynamic function of formation of alloy (i - Na, K, Cs etc.)
ΔZ^*	- $= \Delta Z - \Delta Z_{ideal}$, excessive integral function of formation of alloy
ΔZ_i^*	- excesive partial function of formation of alloy
γ	$= a/x$, activity coefficient
δZ	- relative error of function

3. Introduction.

Energetic power installation of a big

orbital station consist of fast neutron nuclear reactor, built-in thermoemission generator and system of cooling. The last contains a main liquid-metal high temperature loop which is cooled with help of a pack of high temperature liquid-metal heat pipes. For initial fast preheating of the cooling system during setting it in motion after cold condition there is a special loop filled by low-melting liquid-metal coolant. This coolant (three component eutectic of system Na-K-Cs) is universal one and suitable not only for reactor-generator but for solar power sourse too.

Binary and ternary systems of alkali- and alkali-earth metals as coolants reserving all the advantages of pure components, acquire additional merits:

- maximum broad diapason of working temperatures of liquid phase being both high temperature- and low-temperature coolants simultaneously;
- possibility of regulation of thermo- and electrophysical properties by varying of components fractions.

For example, with help of certain regulating of fractions it can be obtained the compositions corresponding to special points of phase diagrams which have extraordinarily low temperature of cristallisation ($t \approx -80^{\circ}C$).Such temperature is the minimum one for all the metal liquids known in the world, and the coolant remains in liquid state at any earth conditions. The task of this investigation was the obtaining of correct thermodynamic discription of binary and ternary named liquid-metal systems as a basis of coolants of the new kind - with regulated properties. This discription means building of the set of characteristical functions (potentials) which in coordinates P,T,x_i are Gibbs energies of formation of the systems (partial and integral functions, full and excessive values, activities of components: $\Delta\bar{G}_i$, ΔG, $\Delta\bar{G}^*_i$, ΔG^*, a_i, γ_i) and their derivatives (i.e. the rest thermodynamic functions which are enthalpy and entropy of formation, excessive heat capacity: $\Delta\bar{H}_i$, ΔH, $\Delta\bar{S}_i$, ΔS, $\Delta\bar{S}^*_i$, ΔS^*, ΔCp) - in the area $0\leqslant x_i\leqslant 1$, $200\div400K\leqslant T\leqslant 1200\div1500K$.

Direct measurement of change of partial Gibbs energy of components at formation of liquid-metal alloy in broad temperature diapason, which would be performed by EMF-method[1-4], is extraordinarily difficult because of absence of steady high-temperature solid electrolites with needed ionic composition using as membrane of concentration sells. Determining of partial pressure and activity of components with help of experimental study of absorption spectra by atomic-absorption method[5,6] is limited on temperatures because of influence of radiation contribution of corresponding lines. Effusion methods at high temperatures (with either optic- or mass-spectroscopic or chemical determining of flow composition) are not suitable for alkali-metal systems because of high saturation pressures and technology difficulties of operating with atomic high intensivity flows of alkali metals direct leaving for the area of installation.

4. Method.

Instead of direct measurement of Gibbs energy of alloy formation $\Delta\bar{G}_i$ or activity of components a_i at high temperature it is proposing to realize:

- experimental determining of temperature- and concentration dependencies of enthalpy of formation (heat of mixing) ΔH, $\Delta\bar{H}_i$ in all required diapason of parameters: $\Delta H, \Delta\bar{H}_i=f(x_i,T)$, that is essentially easyer and can be fulfiled in hermetic working cells;
- experimental determining of activity of components a_i or partial Gibbs energy $\Delta\bar{G}_i$ at certain one - not high - reference temperature $T_1 \approx 400K$: $a_i=f(x_i,T_1=const)$ or $\Delta\bar{G}_i=f(x_i, T_1=const)$;
- then solving of differential equation of chemical thermodynamics of type

$$[\partial \ln a_i/\partial(1/T)]_{p,x_i}=\Delta\bar{H}_i/R \qquad (1)$$

$$[\partial(\Delta\bar{G}_i/T)/\partial(1/T)]_{p,x_i}=\Delta\bar{H}_i \qquad (2)$$

where experimental finding values of $\Delta\bar{H}_i=f(x_i,T)$ are using as underintegral functions and $a_i=f(x_i,T_1)$ or $\Delta\bar{G}_i=f(x_i,T_1)$ - as boundary conditions of integration giving the possibility to close the solution, which have a kind:

$$\ln a_i(x_i,T)=\ln a_i(x_i,T_1)-R^{-1}\int_{T_1}^{T}\Delta\bar{H}_i(x_i,T)T^{-2}dT \qquad (3)$$

$$\Delta\bar{G}_i(x_i,T)=\Delta\bar{G}_i(x_i,T_1)(T/T_1)-T\int_{T_1}^{T}\Delta\bar{H}_i(x_i,T)T^{-2}dT \quad (4)$$

Proposed scheme does not require any hard assumings and can be provided with reliable input experimental data.

5. Experimental.

According to the principle of method two groups of installations were in a ground of experiment:

1) a complex of calorimetric apparatus for determining of caloric properties of liquid-metal systems (enthalpy of formation, heat capacity, heats of phase transitions) in the whole area of concentrations and temperatures;

2) apparatus for determining of thermodynamic activity or partial Gibbs energy in the whole area of concentrations at certain one non high reference temperature (T_1=$=const\approx 400K$).

The first group included[7,8] :
a) high-temperature calorimetric installation by mixed method with calorimeter with evaporating liquid (enthalpy, heats of mixing and phase transitions);
b) high temperature installation by puls-differential method (heat capacity, heats of phase transitions);
c) high-temperature adiabatic reaction calorimeter for measuring of enthalpy of formation of systems with number of components from 2 up to 4 ($n+k=5$, where n - number of components, k - number of compositions under the test in one experiment) in the whole area of concentrations and temperatures;
d) adiabatic reaction calorimeter of constant temperature for measuring $\Delta H=f(x_i,T_1=const\approx 400K)$.

The second group included[9] :
a) installation for determining of thermodynamic activity of components in binary and multicomponent liquid-metal systems by effusion method on partial pressure of saturation vapour obtained by measurement of intensivity their atomic flows with making of effusion orifice with help calibrated electron-beam pulse generating directly in vacuum chamber of installation (when the hermetic effusion cell has reached the required working temperature);
b) installation for determining of necessary accomodation coefficients by method of vaporisation from open surface of garnisage crusible with using of electron-beam bombardment in unbroken regime as source of surface heating.

6. Results.

The enthalpy of formation at all the concentrations and temperatures and the activity of components at all the concentrations and one temperature $T_1=400K$ were measured. Then in accordance with discribed method by solving of eq. (3) or (4) the activity (and Gibbs energy) at all the concentrations and temperatures was calculated and the rest thermodynamic functions was obtained with help standard relations:

$$\Delta\bar{G}_i(x_i,T)=RT\ ln\ a_i(x_i,T);$$

$$\Delta\bar{G}_i^*(x_i,T)=RT\ ln\ \gamma_i(x_i,T);$$

$$\Delta\bar{H}_i(x_i,T)\equiv\Delta\bar{H}_i^*(x_i,T)=\Delta H+\frac{d\Delta H}{dx_i}(1-x_i)=\left[\frac{\partial(\Delta\bar{G}_i/T)}{\partial(1/T)}\right]_{p,x_i}=\left[\frac{\partial(\Delta\bar{G}_i^*/T}{\partial(1/T)}\right]_{p,x_i};$$

$$\Delta\bar{S}_i(x_i,T)=-[\partial(\Delta\bar{G}_i)/\partial T]_{p,x_i}=\Delta\bar{H}_i(x_i,T)/T-R\ ln\ a_i(x_i,T);$$

$$\Delta\bar{S}_i^*(x_i,T)=-[\partial(\Delta\bar{G}_i^*)/\partial T]_{p,x_i}=\Delta\bar{H}_i(x_i,T)/T-R\ ln\ \gamma_i(x_i,T);$$

$$\Delta C_p=[\partial(\Delta H)/\partial T]_{p,x_i}=T[\partial(\Delta S)/\partial T]_{p,x_i};$$

$$\Delta Z(x_i,T)=\sum_i x_i\Delta\bar{Z}_i(x_i,T);$$

$$Z(x_i,T)=\sum_i x_i Z_i^o(T)+\Delta Z(x_i),$$

$$\bar{Z}(x_i,T)=Z_i^o(T)+\Delta\bar{Z}_i(x_i,T).$$

The data for binary and ternary systems Cs-Na, K-Na, Cs-K, Cs-K-Na, Ba-Cs, Be-Ba, Be-Sr, Be-Ca, Be-Mg, Ca-Sr, Ca-Ba, Sr-Ba, Mg-Ba, Mg-Ca and so CsF-Cs and Li-H (lithium hidride) was obtained. The functions (from liquidus line up to 1200-1500K) are figure 1.

7. Discussion.

Model theories was used as instrument of interpretation of the ontained experimental data and ground of their adequate approximation. For the enthalpy of formation - quasichemical model proposed by Guggenheim[10] and developed for these liquid-metal alloys[11] taking into account the alteration of short-

-range order structure comparatevily with chaotic distribution as well as concentration and temperature dependences of energies of all kinds of pair interparticle interactions (e.g. three kinds for binary systems). For entropy of formation (obtained as the difference between experimental values of Gibbs energy of formation and enthalpy of formation) - hard-sphere model with a little dependence of hard-sphere diameters on concentration[12] as fitting parameter of theory.

On the basis of analysis of long-wave limit of concentration correlation function $S_{cc}(0)$[13] :

$$S_{cc}(0)=\langle N(\Delta x_i)^2\rangle = RT(\partial^2\Delta G/\partial x_i^2)^{-1}_{p,T} = RT[(\partial\Delta\bar{G}_i/\partial x_i)/(1-x_i)]^{-1}_{p,T} = [(\partial \ln a_i/\partial x_i)/(1-x_i)]^{-1}_{p,T} \qquad (5)$$

which was computed for all area of temperatures and concentrations (for binary systems of alkali metals up to 1200K - see figure 2) with help of obtained thermodynamic data, these results were compared with available literature data (at T≈400K) of difraction experiment (structure factor $S(0)$)[14,15] as well of some thermodynamic experiments[1-6] and calculations[4,12]. There was an accordance concerning the magnitude and coordinate of maximum of function $S_{cc}(0)$ [$0,7\leqslant x_i\leqslant 0,8$ for system Cs-Na - eq.(5), fig.2]. It corroborates existance of concentration long-range fluctuations in some liquid-metal systems, i.e. micro-non-homogeneous (claster) structure of liquid alloy and therefore decreasing of thermodynamic stability of system as homogeneous liquid phase. This fact correlates with phase diagrams, e.g. for Cs-K system liquidus-line in named concentration range is practically horizontal, i.e. increasing of concentration fluctuations pointed out the tendency to phase stratification[3,4]. Some peculiarities of behaviour of thermodynamic functions are discovered - inversion of Gibbs energy, entropy, activities in deviation from Roult's law. This phenomenon is analogous to inversion of compressibility factor for one-component liquids in area of negative values of second virial coefficient. Correspondingly to these results mutual alloys of studied metals are not only nonideal solutions but being real solutions displayed different thermodynamic classes of them depending on temperature and size factor[11]. The analysis gave the possibility to separate the ranges of existance of each class and particularly to explain the anomaly in deviation from Roult's law which have been displayed in independent measurements of saturation pressure[16]. The results on concentration and temperature dependences of short-range order parameter, energies of interparticle interaction, concentration correlation function explain the contraction of studied alloys[17], anomaly in acoustic[18], electromagnetic[19] properties and NMR-spectra[20], display the correlation with phase diagrams and point out the certain possibility of prognosis of some liquid-metal system properties are demonstrated.

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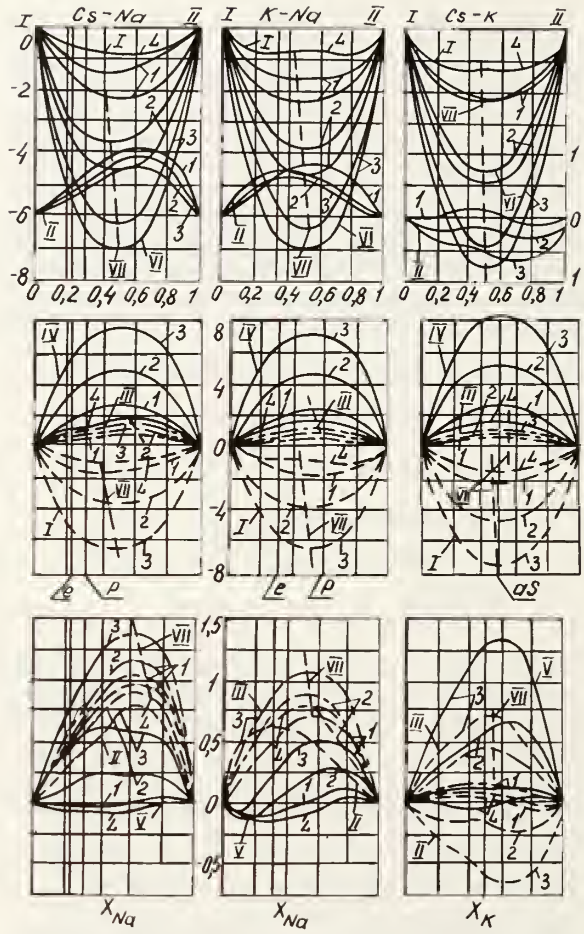

Figure 1 - Thermodynamic functions of systems, kJ/g-atom

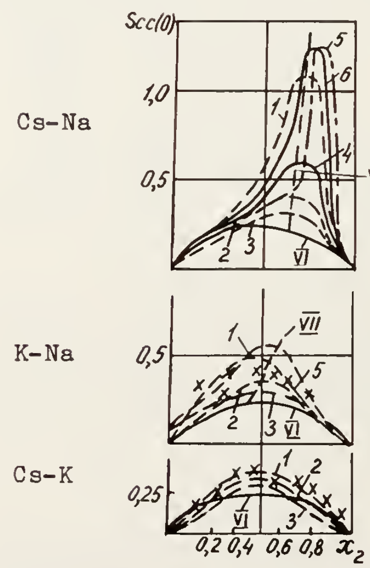

Figure 2

Concentration correlation function from 400 up to 1200K

1 - 400K, 2 - 800K, 3 - 1200K.

4 - 473K[4]; 5 - 383K[3], 6 - 383K[4], x - 373K[14].

I - Δ G, II - ΔG^*, III - ΔH, IV - TΔS, V - TΔS^*, VI - ideal mixture, VII - extremum line, e - eutectic, p - peritectic, as - aseotropic, L - liquidus.

B6.1 Prospects for inexpensive space transportation

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Summary

In this paper the author argues that it is now possible to reduce the cost of transportation from earth to low Earth Orbit by about 2 orders of magnitude. He explains why costs have been high until now, why these can be reduced dramatically, and what is now being done in America to do this. He concludes that this development, alone, should greatly improve the prospects of deploying economically viable solar power satellites (SPS) and other space-based systems.

Résumé

Dans cette étude, l'auteur fait le point sur la possibilité de réduire aujourd'hui les frais de transport entre la terre et l'orbite terrestre basse par presque deux ordres de magnitude. Il explique les raisons pour lesquelles les prix sont restés si élevés jusqu'à maintenant, comment on peut les réduire d'une façon significative et quelles sont les démarches aux Etats-Unis qui ameneront à une réduction des frais. Il conclut que cet effort seul devrait améliorer les possibilités de mettre en oeuvre économiquement les SPS et autres systèmes spatiaux.

I. Background

Space is the most recent area that industrialized nations can exploit for economic, political, social, and security purposes. While technological progress opened up access to space over 35 years ago, even the most developed countries have only begun to realize the benefits for life on Earth that lie beyond this high frontier.

The era of discovery and exploration of near space should change into an era of economic exploitation by the onset of the next century. This will only come about, however, if two inter-related events take place. The first, is the opening up of space to free enterprise, and the second is technological realization of access costs that will permit the private sector to pursue profitable, large scale, business ventures in space. Only when affordable means of getting from Earth to near space and back, become available will the full economic potential of this new frontier be realized.

Until recently most U.S. space activities have been initiated and managed by government. One result of this has been that transportation costs tend to be buried in, or secondary to, the cost of the projects they support. And, since the objectives of the government's programs have been dictated primarily by national interests, such as security or intelligence gathering, they are paid for by the taxpayers and do not have to make a profit. As a result of this, there has been little or no real incentives for reducing transport costs other than in an overall national budgetary context.

While these priorities were logical and understandable in the cold war era, the failure of government funding to give a high priority to reducing lift costs has been one of the major impediments to the civil sector's development of this vast new area. Free enterprise space activities have to pay for themselves and turn a profit and transportation costs are obviously a major factor when it comes to meeting this basic requirement.

I suggest that all this is now about to change. The Cold War excuse for government monopoly of space developments is no longer valid. Obviously any dramatic reduction in travel costs would open up new economic possibilities in space. This would be to everyone's advantage. It would turn overly costly or marginal civil sector ventures, that until now have been dreams or paper studies, into practical free enterprise projects. And, while governments will no doubt still have to pay for

multi billion dollar, high risk, programs such as large power complexes like SPS, asteroid mining, or lunar bases, many less costly activities such as manufacturing in space, new communications systems, and even tourism should attract venture capital and result in industry initiatives.

In 1986 the U.S. National Commission on Space recommended "a U.S. commitment to create and operate systems and institutions to provide low cost access to the space frontier."[1] To achieve this goal they also recommended aggressive development of the technologies for reusable single stage to orbit (SSTO) rocket launch vehicles. Last year a Committee appointed by the Vice President's Space Council to review the NASA space program also called for a new family of launch vehicles.[2]

Unfortunately, the development of economical launch vehicles has not been a matter of priority for either NASA or the USAF. This is no doubt partly due to the fact that neither organization has been specifically charged with helping free enterprise exploit space, and partly to a normal desire to protect their investments in the expensive older Shuttle and Expendable Launch Vehicle (ELV) systems they now use. Fortunately, however, several of America's best known rocket engineers, The Citizen's Advisory Council on Space Policy and High Frontier, a national interest advocacy group in Washington, came together in 1989 to change this situation. Recognizing both the importance and feasibility of building cost effective SSTO rockets they insisted that the government take a more active role in developing these and this is now being done.

II. Possibilities For Cheap Lift

Ever since space became accessible, in 1958, the cost of transporting goods and people from Earth to low Earth orbit (LEO) has been very high. It still is. Conservative calculations in 1988 U.S. dollars for each flight to LEO, equatorial plane, are now approximately $484.00 million on a Shuttle and $145.00 million on a Titan ELV. This works out to 10,803 $/lb on the shuttle and $3718 $/lb on Titans.[3] At these prices the United States spends between one half and one third of its space dollars simply to get to space. These prices have also been the principle barrier to the exploitation of space for many potentially profitable commercial activities.

There is no insurmountable reason why travel to LEO need be so costly. By adopting a "new approach" to vehicle design, utilizing materials and engine technologies recently developed under the U.S. National AeroSpace Plane program (NASP) and designing our space transportation systems to be comparable in reliability, safety, and frequency of service, with commercial air, we should be able to reduce the above costs to under $500 per pound.

Last year, the prospects of doing this within a few years time were sufficiently persuasive to cause the U.S. Defense Department's Strategic Defense Initiative Office (SDIO) to allocate $15 million towards the development of a prototype, SSTO, rocket transport. This work is now well underway led by four major U.S. aerospace corporations and their findings to date are very optimistic.

Today there seems to be general agreement among most of our space experts and engineers that the technology exist to build several types of reusable, low cost SSTO rockets that can be made to operate much like conventional aircraft. Many of those now working with this program are confident that this would reduce the cost of transportation into space by at least 2 orders of magnitude. With only a 4 vehicle fleet this would bring space transportation costs to LEO to well under $500.00 per/lb and per flight costs to about $8 Million.

The SDI contracts call for demonstration vehicles by the mid 1990s and first generation operational vehicles to be flying before the turn of the century. If successful cost reductions of this magnitude could generate an economic revolution in space activities greater than that brought about by jet aircraft. In any event, they will make large space systems such as SPS much easier to deploy and more cost effective, hence more attractive to pursue whether by governments or private investors.

III. Why is Cheap Lift Now Possible?

The initial reaction of most audiences to predictions of such dramatic cost reduction in the near term is incredibility. The first question is invariably, "if this is true why haven't governments involved in space operations done this long ago, or at least moved towards achieving these cost goals?" While it is not the purpose of this paper to detail and defend the specific technologies that now make this possible, a brief answer to this question seems pertinent to persuading those of you now advocating and planning for future space projects, such as SPS systems, not to be discouraged by the current high costs associated with their deployment.

The high transportation costs faced by space operations today can be broken down into two broad categories in terms of their origin. The first are those attributable to technological reasons and the second are those that stem from the

circumstances surrounding the initial space race in the late 1950s and early 1960s.

In the first case—that of technological limitations—the possibility of building low cost, effective, transportation systems was limited by the types and weights of structural materials available in the 1950s and 1960s. It was also limited to a lesser degree by rocket engine technology.

In the second case—the circumstances—the urgency to keep up with Soviet space developments for national security led to using what were essentially modified military munitions—ICBM's with saddles on them—to get into space quickly instead of developing transportation vehicles optimized solely for transportation purposes.

These two conditions led to the development, use, acceptance, and almost standardization of multiple-stage, wholly or partly expendable, rocket systems which were derived from munitions with all their associated risks and costs. Even when technological advances in materials, in the 1970s, started to make single-stage recoverable, reusable, and relatively safe lift systems interesting a combination of resistance to change and demands for ever heavier payloads kept governments from exploiting these advances to develop new types of launch vehicles until now. Once billions have been committed to any one approach to doing anything it is inherently difficult for those involved to start over at the expense of risking their expertise and making the systems they have been accustomed to using.

Another major factor in the high cost of space travel has been that associated with the operations and maintenance (O&M) of the munitions derived systems. Literally, field armies of people are now required to service and operate these. It has been estimated that it takes over 15,000 employees to refurbish, assemble, test, launch and safely supervise and operate a Shuttle flight. This compares to a U.S. airline average of 140 people per aircraft and some 400 people per aircraft for the most sophisticated military systems such as our Blackbird Fleet. Such personnel costs, when coupled with the low turn around rates of shuttles and throw away features of expendable rocket launcher are obviously major factors in their high operating costs.

To minimize costs vehicles designed for any transportation mission, including access to and from space, must benefit from simple designs for ease of maintenance and servicing, provide a reliable abort capability throughout their flight regime in the event of non catastrophic failures, and have turn around times equivalent to aircraft. The new family of SSTO transports we are now developing will meet these criteria.

By some estimates failures on today's launch fleet nearly double national costs of space launches. SSTO rockets can potentially reduce these losses due to their intrinsic reliability. Design now under consideration can loose one main engine and complete their mission or loose two and still safely abort, similar to conventional aircraft. Given these capabilities the savings in insurance alone become substantial.

If the new vehicles are not only designed for safety in all operating regimes but also for rapid refueling, ground processing, and turn around, and to be able to operate with minimum use of unique base facilities and equipment such as assembly buildings and gantries, the potential cost savings are very great. All this can now be done and with existing technology.

IV. Correcting the High Costs

During the 1980s massive U.S. government spending on developments programs, such as the National AeroSpace Plane programs (NASP) and Strategic Defense Initiative (SDI) have produced and tested light weight, re-usable, structures able to both contain cryogenic propellants and withstand the heat of re-entry. The advanced materials these research programs have brought about are ideally suited to SSTO rockets.

Since empty weight drives development, production, and operating costs on both air and space systems the potential for even greater cost reduction should increase as SSTO rocket technology and operations mature. Graphite epoxy, aluminum lithium, titanium metal matrix composites, and aluminum honeycomb panels are now off the shelf materials available to build propellant tanks and space structures. This has all but solved the earlier SSTO weight problems.

By designing for reliability, safety, a minimum of support personnel, and an economical flight rate the SSTO transport will be more like a commercial aircraft than a space booster. Conventional boosters normally now operate with reliabilities of 94% to 96%. The SSTO transports, using multiple levels of backup capabilities to provide intact abort, and including escape- ejection mechanisms for catastrophic failure, should have 99.9% reliability. These safety features also allow progressive flight testing like aircraft thus increasing reliability and reducing gold plating and redundancy requirements.

Unlike ELV's which throwaway everything on each flight, or even Shuttles which toss off tanks and other parts, the SSTO's only expendables will be fuel and propellants used for control along with life support expendables if needed. When one adds to this flight rates of once or twice weekly that spread fixed costs over large numbers of flights cost reduction in the order of 60% over conventional launchers are achievable.

There appear to be no insurmountable problems in devising engines to meet the SSTO requirements. More than adequate progress has been made in rocket engine thrust to weight ratio in recent years. The problem has been the configurations best suited to meet the abort specifications. Current proposals envision engines that can be easily maintained and are structurally efficient. When these are clustered in groups of up to ten modules, each with self contained pumps, combusters, and nozzles, they will provide the necessary redundancy for safe operations, engine out capabilities, and ease of engine change. Modifications to existing engine designs appear to be adequate to demonstrate the first SSTO's even though improved engines made specifically for SSTO operations, will no doubt be built for use in operational systems. All engines will be liquid fueled. Most proposals plan to use inexpensive H_2-O_2 although other fuels are being examined.

We have never before built a rocket ship that you could save if you had an engine failure, and bring it back, repair it, and fly it again. As a result, the problem with engines for first generation SSTO space transports is more one of configuration and throttling of the multiple engine systems required to meet abort and landing requirements rather than one of needing any new developments in thrust to weight ratios.

Looking ahead, it now appears that the inherent scalability of rocket vehicles combined with use of advanced technologies will support larger payloads in later generation vehicles. Even if the SSTO vehicles now being designed can be scaled up to heavy lift payloads in later generations this may or may not prove to be necessary. Instead it seems likely that standardized, reliable, vehicles with twenty to fifty thousand pound lift capabilities should cause payload designers to adjust to their use rather than pay exhorbitant additional costs for larger specialized loads. This is especially true when quick responses and rapid turnaround capabilities will make it easier to assemble structures in space.

V. Making this Happen

Theory as to what can now be done is fine but counting on it being done in order to plan projects that depend on it calls for some evidence that the reduced costs forecast will in fact be realized and in what time frame. Obviously this is what SPS designers are likely to be most interested in.

It is now clear that first generation demonstration space transports able to provide cost effective transport at under $400 per pound, and possibly less, will fly before the turn of the century. This is based not on confidence in the paper proposals and theories of SSTO advocates but on the fact that, at long last, their initial development and demonstration is underway having been funded and contracted for by our Defense Departments SDI organization in early 1990.

While there is still debate as to the specific characteristics and architecture of these specialized space transports, and what their initial payload capabilities will be, all those involved appear to be convinced there are no technological problems not readily resolvable. The SDI contractor programs are now approaching their Phase II task—that of designing a full, or possibly sub scale vehicle. In Phase II, which will start this summer assuming it is adequately funded, one or more orbital or sub-orbital vehicles will be built and tested.

The key requirements these must meet are:

(1) A medium payload to orbit of 15,000 to 20,000 lbs including crew members;

(2) A turn around time of 7 days or less with surge capability and no more than 350 mandays of support per flight;

(3) High reliability: short flights with an engine out, all altitude abort and crew ejection.

The SSTO fleet is being designed to be both man and non man rated and flight certified from the onset just like commercial aircraft. We are looking for the option of deploying a fleet of these mini vans by the turn of the century. The first fleet is being funded and developed by SDI in order to reduce deployment costs for Brilliant Pebbles, the space based layer of SDI's defenses. Many believe that if and when it demonstrates the ability to meet the goals I have outlined new transportation service companies will enter the space travel field and industry will compete to provide these with the low-cost, safe, and reliable vehicles they will be shopping for. The SSTO promises to become the Space DC-3 or 747 of the 21st century.

VI. Additional Advantages

One major advantage that SSTO transport will enjoy over existing expendable systems lies in their flexibility when it comes to both lunch and recovery sites. Because the new transports drop nothing on their way to orbit and back, and are capable of returning to base or continuing on their missions under emergency abort conditions, and need no highly specialized and exotic ground facilities, they will be able to operate off inland bases as well as on the coast with no more risk to those below than presented by today's aircraft. This in itself will reduce costs for their users if not their operators.

The availability of inexpensive specialized space transports will not necessarily obsolete heavy lift vehicles such as the Shuttle. It could however change their role somewhat. Shuttle vehicles while expensive, complex, and risky as transports to and from space also serves as space laboratories once in orbit. While criticized as a cost effective transport its usefulness to do more than merely carry people and equipment is unquestioned. In this last role the longer it could stay in orbit the more cost effective it will become. The only limiting factors here are resupply of expendables, replacement of crews, and removal of waste. If a cheap transport SSTO rocket can act as a ferry for resupply the shuttles could stay in orbit for weeks or more on tests and tasks of the type envisioned for the space platform. Those of us who advocate the new SSTO transport systems have not persuaded NASA of this yet but we are working on it!

Another important characteristic of the family of SSTO vehicles now on the drawing board is their likely versatility once in space. Unlike Shuttles or expendable rockets if refueled in orbit they can operate effectively anywhere in cis-lunar space as well as land on the Moon. This suggests that even first generation models will be able to deliver cargo beyond LEO if refuelled in space. As such they should eliminate the need for secondary lift systems—space tugs—to do this for solar energy projects like SPS.

VII. In Summary

We now have a new family of space transports under development that should provide reliable, low cost transportation to and from low Earth orbit. This should make the frontier of space affordably accessible for the benefit of all friendly nations and establish a new space highway over which space commerce can flourish. This system is currently referred to as single-stage-to- orbit (SSTO) space transportation vehicle.

The SSTO will initially be a medium lift (10 to 20 thousand pounds of cargo) low mass, reusable, transport that can be scaled up for heavy launch requirements in later models.

By being designed for ease of maintenance, efficient vehicle ground service systems, automated mission planning, and containerized payloads the new space transports can be regularly turned around in a few hours or days depending on mission needs and fleet sizes.

These vehicles can now be built by taking advantage of new, lightweight proven structural material design. This should result in vehicles able to deliver payloads as a ratio to their empty weight, comparable to today' aircraft. By keeping down empty weight and operations and maintenance costs and personnel requirements, and emphasizing reusability and saveability these transports will greatly decrease travel costs to and from space.

There is no reason why the new family of SSTO vehicles cannot be operational by the late 1990s. Their availability should open up space not only to the private sector for commercial ventures but also to the public by making activities such as tourism economically feasible. They will also obviously change government attitudes appropriating moneys for obtaining new sources for vital resources from space such as solar energy or rare metals on asteroids. This will create new opportunities for adventure and open up new industries and new sources for creating wealth and/ or providing cost effective national security for spacefaring nations on Earth.

Footnotes:

1. U.S. National Commision on Space, 1986 Report, Dr. Thomas Payne, Chairman, Washington, DC.

2. Report of Advisory Committee on the Future of the U.S. Space Program, December 1990, U.S. Government Printing Office, Washington, DC 20402.

3. Hoeser, Steve, "The Cost Impact of True Spaceships," *Journal of Practical Applications in Space*, Vol. 1, No. 4, High Frontier, Inc., 2800 Shirlington Road, Suite 405A, Arlington, VA 22206.

B6.2 SPS transportation requirements: which launch system?

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SUMMARY

The need for low cost, routine and reliable access to space is discussed in the context of the proposed Solar Power Satellites. It is shown that in almost every respect, the transportation requirements for SPSs are diametrically opposed to the World's existing launch capability, and the restrictive nature of these launchers has a profound impact on the payload design and mission configuration. Three different SPS scenarios are discussed in relation to their individual launch requirements. These three scenarios are: 1) small demonstration experiments, 2) inter-satellite space power stations, and 3) the full-scale SPS for terrestrial power needs. Finally, new launcher concepts presently being developed, including aero-space planes and heavy-lift boosters, are discussed to determine their applicability to the various defined SPS scenarios.

(*Note : The views expressed in this paper do not necessarily reflect those of CREST.)

RESUME

Le besoin d'un accès peu coûteux à l'espace de façon fiable et régulière est abordé ici dans le cadre des SPS (Solar Power Satellites). Il est clair que les besoins des SPS en matière de transport sont radicalement opposés aux capacités actuelles de lancements, mais également que les performances limitées des lanceurs ont une grande influence sur la conception des charge utiles et sur la définition des missions. Trois scénarios relatifs aux SPS sont discutés, chacun par rapport à ces spécifications de lancements : 1) expériences de faisabilité à échelle réduite, 2) transfert d'énergie inter-satellite, 3) un SPS opérationnel pour des besoins terrestres d'électricité générée dans l'espace. Enfin, les concepts de nouveaux lanceurs en cours de développement, comprenant les avions spatiaux et des lanceurs à très grande capacité, font l'objet d'une discussion pour déterminer leur compatibilité avec les scénarios SPS mentionnés.

1. Introduction - The Need for Accessibility

The successful technical and economic development of the proposed Space Power Stations and Solar Power Satellites (SPSs) (1) will hinge entirely on the ability to place personnel and cargo in space as and when required, reliably, and at very low costs. Whether it is the construction of an inter-satellite space power station for the transmission of power on the order of 100 kW to an in-space user, or the beaming of several 'GWs' of power to the Earth for terrestrial consumption, every option will require the same type of transportation services as are taken for granted on Earth. For example, during the construction of a power station on Earth, materials are brought to the construction site using a variety of vehicles including trains, trucks, and aircraft. Likewise, it is important that a large work force can be accommodated nearby, that transportation services are available to allow the staff to get to the site, perhaps using cars, and that the necessary systems are available to maintain the proper working conditions. In addition, when a problem arises during construction and operations, access to the area concerned is seldom a major inhibitor to the power station.

When attempting to understand the requirements for space transportation, the critical issues in the development of large space structures are considered to fall into the following generic categories:

Continuous access : Large scale manned spaceflight activities like the SPS differ significantly from most other smaller-scale operations because each element has to depend upon one or more other elements functioning properly. This differs fundamentally from the more classical space programs, such as communications and science satellites, that must carry all the systems needed to support their entire mission. Continuous access is needed to supply hardware elements, logistics, spare parts for routine and unexpected maintenance, and the construction staff. Supply of each will need to start with the first element launch and continue thereafter on a regular and reliable basis over the life-time of a particular SPS system.

Failure resilience : Regardless of the effort put into a program like SPSs, failures - although "probabilistic" - are inevitable. Such failures can range from the loss of a major system, to the malfunctioning of individual components within a system. The more resilience or robustness that is built into the program from the beginning, the higher the probability that operations will be allowed to proceed despite such failures. Alternatives, where reasonable or needed to enhance safety, should always be available. Clearly, because of the requirement to maintain a continuous access for SPS construction and operations, as described below, the need for resilience is a fundamental prerequisite.

Orbital testing. Another potentially critical concern relating to continuous access is the ability to test under the proper conditions. Developing subsystems, systems and operational procedures for space applications usually demands repeated testing to the "edge of the envelope." Failures that occur during traditional test campaigns are usually the only method of fully characterizing the performance of a particular piece of hardware or operational procedure. Indeed, hardware that is not rigorously tested may cover up inherent design flaws that could lead to later failures. Obviously, from an engineering standpoint, the most prudent method of verifying SPS hardware and procedures, especially complex systems like a microwave power transmission antenna or automated construction vehicle, is to repeatedly test them in orbit.

Throughout the paper, discussion will focus on the impacts the choice of launch system has on possible SPS activities within the general context of those issues relating to continuous access, failure resilience, and orbital testing.

2. Charateristics and Impacts of Current Launch Systems

Accessing space is technically an extremely demanding activity. However, seen from a functional perspective, space transportation is, fundamentally, no different than any other form of transportation, such as airplanes, cars and trains. As a service, space transportation must follow the same rules as the others: the less they are restricted, the easier space operations are likely to become. Thus, launch vehicles should be designed solely to meet the objectives of satisfying the needs of the users. Although there are very significant technical and economic constraints that limit the choice of possible launch vehicle options, for the majority of users, including potential SPS developers, the most desirable requirements are :

- availability at short notice or 'on-demand'
- a large number of launch opportunities each year
- very high probability that the payload can be reliably recovered following and during a launch abort
- wide selection of orbits
- a selection of launch sites
- the ability to service or recover payloads in orbit
- back-up launch capability
- large volume for the payload
- large payload mass
- a benign launch environment

All of these requirements are dominated by how affordable the launch system is. Clearly, if a new launch system is conceived to maximize all of these requirements to the advantage of the user - while achieving the lowest sensible launch cost - then this will provide the most suitable environment conducive to promoting space operations. An affordable, user friendly launch vehicle is considered a fundamental prerequisite to enhancing the potential for expanded utilization of space including the SPS, as will be discussed in Section 3.

The West has a wide variety of launch vehicles ranging, for example, from *Ariane 4* and *Atlas* for medium payloads to the *Titan 4* and Space Shuttle for large payloads. These vehicles are characterised by the following :

- high yearly operating costs from $ 1- 5 billion, (fixed & recurring),
- high operational costs from $ 60-1000 million per flight,
- relatively low reliability from around 90-98%,
- no abort capability, except for some Shuttle cases,
- low flight rates and launch opportunities of 5-10 per year,
- long lead times from purchase to launch of about 2-3 years,
- frequent delays measure in weeks, months or even years,
- long stand-down times after failures (months or years),
- few servicing or payload recovery opportunities (STS only, 2-3 years wait),
- limited launch sites.

Compared to the requirements discussed for current launch systems, it would appear that virtually all the capabilities of current launchers are diametrically opposed to those demanded by the user. Current launchers, for example, can provide suitable capabilities in the areas of payload size and mass. However, these capabilities must be considered in conjunction with the other launcher characteristics. For example, large launcher payload mass and volume capabilities could facilitate the construction of highly modularised, serviceable and recoverable spacecraft, such as inter-satellite space power stations (Section 3.2). However, without the means to rendezvous with such spacecraft, and when necessary, the serviceability aspect becomes irrelevant. The recent (1990) destructive re-entry of the serviceable *Solar Maximum Mission* satellite is an appropriate example.

The impacts of current launch vehicles on missions and payloads is summarised diagrammatically in Figure 2-1. If launch costs are high, and there are limited launch opportunities available, then the first impact is to restrict the number of users that can afford to purchase launch services. Of these, the remaining users can usually only afford to purchase the minimum number of launches, leading to smaller production runs for the launch vehicle manufacturers - further raising costs and limiting launch opportunities.

The ability to purchase only the minimum number of vehicles tends to force the user to perform the mission objectives with the minimum possible number of independently functioning spacecraft (e.g. direct broadcast and Earth resources satellite constellations consist of 2 or 3 satellites.) Thus, because only a few spacecraft are used, this forces the manufacturer to construct very highly integrated and lightweight spacecraft which are very reliable and have long mission lives. These are conflicting requirements which inevitably leads to delicate and very expensive products and, like launch vehicles, produced in very small quantities. For example, a typical commercial communications satellite costs anywhere from $ 50-100 m while non-commercial satellites, such as Earth resources and astronomical satellites, can cost anywhere from $100 m to in excess of $1,000 m, as is the case with the *Hubble* Space Telescope.

Finally, because the value of the spacecraft is so high, the user will demand the highest probability of success from the launch services supplier. This also will tend to further raise launch costs, and thus complete the vicious circle. The performance and cost of today's launch vehicles, and the design of the spacecraft which ride them are intimately entwined. From an economic and technical perspective, current launch vehicles are considered the weak link in the chain to enhancing space development. As long as launch opportunities are limited, have a relatively low probability of achieving orbit and the cost of purchasing launch services remains so high, the development of space cannot be expected to expand much beyond current activities simply because the global financial burden - launch and spacecraft costs - is so extreme. Consequently, the impacts of current launch vehicle capabilities is to severely restrict the growth and effective utilization of space.

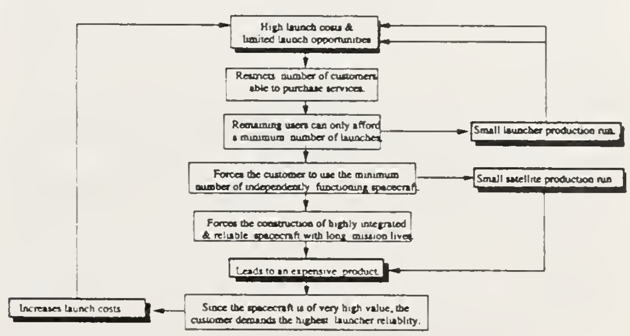

Figure 2-1 : Impacts of Current Launchers on Payloads

3. Launch Requirements as a Function of SPS Scenarios

This section will take a typical SPS evolutionary approach as a basis for developing an appreciation of likely launch system requirements.

3.1 Demonstrators

The critical first step in the evolution of the SPS is the demonstration that modest power levels can be efficiently transmitted across an extended distance and for a sustained period of time. Typically, such demonstrations might involve the launch of two spacecraft, one which is the transmitter and the other the receiver. These two spacecraft would transmit perhaps a few kilowatts of power over distances of several hundred meters, and demonstrate the ability to maintain the proper direction and control of the power beam while the two vehicles orbit the Earth in formation.

The function of such a demonstration will determine its launch requirements. For example, if it is intended purely as a one-off experiment, that is not tied to a larger program aimed at developing an large operational system (Section 3.2), then potentially two satellites could be launched together on a current generation of expendable rockets such as the *Titan 4* or *Ariane 4* and, after the experiment is completed, the satellites would destructively re-enter. Using existing launchers would inevitably lead to an expensive program because of the effort required to ensure that the mission will be a success when it is finally launched, as discussed in Section 2. Very approximately, the cost of such a mission might be on the order of $500 million of which launch costs might consume 25-50%. Further, because of this, the time required before such an experiment is launched might be on the order of 5-10 years, as is typical will complex system such as the *Hubble* Space Telescope, *Eureca*, ERS-1 and so on. In addition, delays of several years are likely and have to be tolerated.

In order to prove the technology and systems required for later cost effective, operational systems, almost certainly a considerable amount of orbital testing will be required, just as testing on Earth is required for ground-based power systems. In this case, launching expensive, expendable experiments that may take many years to complete, is clearly not practical. What is necessary is the ability to launch the test hardware, determine its performance characteristics on orbit, then return it to Earth for modifications before it is relaunched for further development tests. Such hardware could range from the testing in space of components like a magnetron, to full-up system testing of power transmission and reception. (Alternatively, the hardware could be modified on orbit, but only provided appropriate facilities and equipment are available.)

Potentially, the Space Shuttle would seem to be the ideal sort of vehicle for such a mission and a number of comparable missions have been performed, such as the deployment and retrievable of the MBB *Shuttle Pallet Satellite* (SPAS). Unfortunately, it would not be credible to base a rigorous test program around the use of the Shuttle. This is because the Shuttle can only be launched very infrequently (perhaps 5 to 10 flights per year), making regular access to the Shuttle very unlikely. Certainly, should Space Station *Freedom* be built, the Shuttle availability will be all but eliminated. Not insignificantly, the cost of one Shuttle mission is on the order of $500 million (2).

<u>Summary</u>

- For a one-off experiment :
  - Current launch systems will suffice,
  - But will be expensive, expendable, and risky.
- For development testing:
  - Lowest possible launch costs,
  - Regular flights as demanded by the program (monthly),
  - Modest payload performance (several tonnes),
  - Capability to return payloads to Earth,
  - Simple integration facilities,
  - Crew interaction desirable if the cost impact is small.

In summary, for anything other than one-off experiments, a new available, reliable and affordable launch system is required that is fundamentally different to all existing systems.

2.2 Inter-Satellite Space Power Stations

Inter-satellite space power stations for transmitting power on the order of 100-1000 kW to space stations and other platforms should only be developed if there are no other economic alternatives. For example, such power stations have been proposed to augment both the Space Shuttle and space stations (e.g. *Freedom* and the *Columbus* Free-Flyer). However, the low Shuttle flight rate and recent space station de-scaling exercises, appear to have all but precluded the development of an inter-satellite space power stations simply because its would not be possible to take advantage of the extra power available - even if it could actually be launched and supported by the Shuttle. For example, the current *Freedom* baseline calls for the use of a passive thermal control system. Therefore, *Freedom's* thermal control system would be incapable of handling a significant increase in the power supply. *Freedom* was originally intended to include an active and expandable fluid loop thermal control system. However, it was deleted to save funds, and its restoration today would require significant redesign and the incorporation of larger radiator areas. This is consider very unlikely in view of *Freedom's* current technical and funding problems.

For the reasons outlined in Section 3.1, the development of operational inter-satellite space power stations will almost certainly require the development of a new economic, highly available, and reliable launcher. A launch system with these characteristics is critical, not only to the development and construction of inter-satellite space power stations, but equally as critically their support and maintenance. These large structure, with masses on the order of 20-25 tonnes, will inevitably require routine maintenance and repairs as electrical and mechanical failures occur - just as any terrestrial system requires for proper functioning. It would be completely unrealistic to expect such complex systems to function perfectly over many years without requiring maintenance and repair. Indeed, requirements to do so would lead to extremely expensive systems just as is the case today with the majority of satellites. At the very minimum, regular refuelling of the power station will be necessary to allow it to reboost and remain in formation with the user spacecraft.

A new launch system might make the inter-satellite space power station appear more feasible for a number of reasons. Firstly, because of the technical realities of building and supporting such complex structures. Secondly, a new launcher might not only make space power stations feasible, but would also enhance the general use of space for the same reasons, thus increasing the potential market (3). However, this argument can also be viewed from a different perspective. If a new launch system was available, the cost and technical difficulty of increasing the size of the power supply system already attached to the individual user platform, would also decline. There is an optimum point when inter-satellite space power stations become economically feasible. This would seem to occur when the number of users that require high levels of extra power for short periods, increases to the point where the cost to the user of 'purchasing' the power from a power station is less than the cost of increasing the size of the user's own dedicated power supply. Clearly, the price of buying power must be within credible economic constraints of the space power station operations.

Summary

It is considered that:

- Current launch systems alone are inadequate to develop, launch and support a modestly size inter-satellite power station and that a new launch system will be required,
- This launch system should have the same requirements as that described in section 3.1,
- In addition, a back-up or alternative launch capability is necessary,
- The economic operations of such systems must be weighed up against alternatives dedicated to the user's needs,
- The market for space power is likely to increase if a new launch system is able to drastically reduce launch costs,
- Potentially, the growth of the market may increase to the point where it becomes economic for the user to purchase power from a power station.

Again, the successful development of an inter-satellite space power station appears critically dependent on the availability of a new launch system.

3.3 Solar Power Satellites

The justifications for SPSs capable of beaming several GW power levels to the Earth, will be driven by economics in parallel with the environmental desirability of such systems compared with conventional terrestrial alternatives. If the amortized cost of manufacturing and supporting each SPS was, very roughly, one or more orders of magnitude greater than the cost to manufacture the best terrestrially-based system, then their viability might be questionable. Less than this, then their application might be viable simply because it would reduce the dependence on fossil and nuclear fuels, even though it still might be more expensive.

Getting to a situation where SPSs can be built economically will not be easy. While the basic requirements for development, assembly and operational support are the same as inter-satellite space power stations, the difference is the size and mass of the SPS. Typically, an SPS capable of delivering 5 GW of power may have a mass of some 100,000 tonnes in GEO (4). To put this in perspective, after about 3,500 launches, the total equivalent amount of payload mass launched into LEO since *Sputnik 1* is approximately 30,000 tonnes - only about one third that of one SPS. If the materials for an SPS were launched entirely from Earth and assembled over 5-10 years, the World's launch capacity would have to be increased by at least an order of magnitude just for the SPS materials alone (from 1,000 tonnes per year to around 10,000-20,000 tonnes per year). If several SPSs were under construction simultaneously, as almost certainly would have to be the case, then this launch rate might need to be increased by another order of magnitude. Clearly, the means is required to facilitate the uninterrupted, continuous supply of large amount of materials over short periods of time. It is for this reason why consideration has been given to the extraterrestrial supply of materials, such as from the Moon.

The next problem is one of economics. Suppose, for example, to be economically viable the cost of an SPS was about 3 or 4 times that of a nuclear power station, about $20 billion, and transportation costs consumed perhaps a third of that, about $7 billion. Hence, very simplistically, the average cost of launch services would need to be on the order of about $50 per kilogram to meet this target. This is regardless of whether the materials are supplied from the Earth or extraterrestrially.

The final problem revolves around the infrastructure required to handle such a large construction as an SPS, which typically may cover an area as large as 50 square kilometers when completed. Critically, the requirements to support this infrastructure are likely to just as demanding as those to support the SPS itself, with the exception that there will be a significant need for a large human presence. If, for example, the final construction were to be completed in GEO, then vehicles capable of routinely cycling crews, logistics and spare parts from Earth orbit or a Lunar Base to the SPS construction site, will be necessary - at least during the construction of the first SPSs. The cost of establishing this infrastructure will be enormous, especially if extraterrestrial materials are used, and it may well be the single greatest expense in the development of the SPS. This investment, of course, is only justifiable if it can be amortized over a number of SPSs.

Summary

From this discussion, it is considered that :

- A launch system with the same requirements as defined in Sections 3.1 & 3.2 is mandatory just to support the in-space (e.g. LEO, GEO, Lunar surface) infrastructure needs and some of the critical SPS systems that must be supplied from Earth,
- The ability to transport several 'tens of thousands' of tonnes to the assembly sites continuously and without interruption over several decades, either from the Earth or other extraterrestrial sources, is necessary,
- The cost of establishing and supporting the in-space infrastructure will be very large.

4. Transportation System Options

This section discusses the suitability of some of the proposed future Earth to orbit launch systems currently under definition and development that potentially may be able to meet some of the requirements discussed in the various SPS scenarios outlined in Section 3.

4.1 Aero-Space Planes

For all the conceivable SPS missions, except the one-off type demonstrators, it seems clear that a launch system with characteristics closer to an airplane than a rocket is essential. Such a vehicle should be able to fly to and from orbit reliably, as required by the users needs, and at a dedicated launch cost perhaps one or two orders of magnitude below existing systems. The aero-space plane (ASP) is one concept for a space transportation system that may be able to meet these requirements. The desirability of such a launcher has been long recognized. For example, Rockwell International proposed a vehicle called *Star Raker* in the early 1979 for the deployment of a 10 GW SPS. Aero-space planes like *Star Raker* come in many configurations but, in general, they are fully reusable, highly maintainable, one or two-staged winged vehicles capable of taking-off and landing horizontally. A number of studies have shown that this type of configuration is critical to significantly reducing dedicated launch costs (5), but it also recognized that achieving such a capability is an immensely difficult technical task.

The advantage of the aero-space plane is that it provides the type of vehicle that is capable of reducing the cost to orbit while, simultaneously, increasing reliability and availability compared with existing launchers. *Costs* can be reduced because the vehicle is fully reusable, smaller ground crews are needed, and major components to not have to be manufactured and qualified before every mission. *Reliability* is enhanced because the vehicle can be incrementally and repeatedly tested. In addition, should an engine or other system fail during ascent, the vehicle would be able to abort the mission and return to Earth for repairs. This contrasts sharply with all current launchers (except the Shuttle in some cases) which must either reach orbit every time or catastrophically fail.

Finally, *availability* is enhanced because of the minimal work required to turn the vehicle around. Also, the increased reliability (abortability) allows higher flight frequency because the individual characteristics of the vehicle are better understood. It is seldom appreciated that availability is fundamentally tied to flight experience.

A number of ASP programs exist today with the most notable being the *NASP, HOTOL* and *Sänger* Programs. For background, the key features of each are summarized.

NASP & NDVs

Since 1986, the US Government and industrial contractors have spent nearly $2 billion on the *National Aero-Space Plane* Program which intends to develop an *experimental* aircraft - the X-30 (Figure 4-1) - capable of reaching orbit with a single-stage and breathing air to the highest possible speed (6).

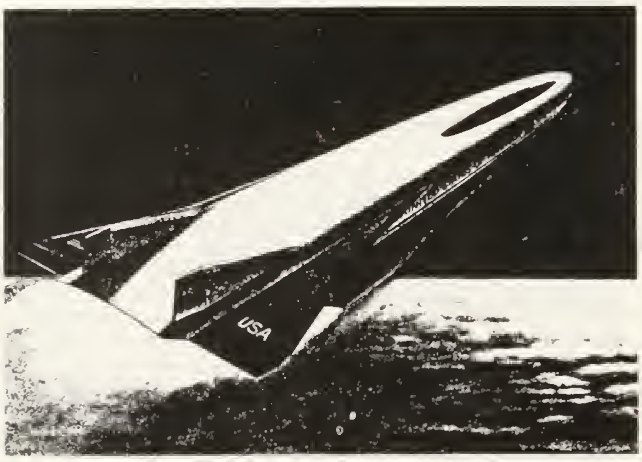

Figure 4-1 : The X-30 National Aero-Space Plane

NASP is generally regarded as a very technically challenging project and it is well known within the aerospace community for its research in the areas of advanced materials, supersonic combustion ramjets, computational fluid dynamics and systems integration. The X-30 is intended to be used as a test-bed for understanding the problems associated with developing an airbreathing single-stage-to-orbit vehicle. It will therefore lay the ground work for the eventual production of an operational fleet of aero-space plane launch vehicles, the *NASP-Derived Vehicles*. Presently, the "reference" NDV is designed as a highly maintainable vehicle capable of being turned around in a few days or hours, and able to place payloads of about 10 tonnes in orbit at a cost of between $1-10 million (7) per launch, based on about 50 flights per year and a loss reliability of better than 99.5%. The *NASP* Program is midway through Phase 2, with funding running at $258m this year, and a decision in Mid-1993 is scheduled to be made to develop the first two experimental vehicles. Aftei this, it is estimated that an operational *NDV* could gradually replace the Space Shuttle before the end of the next decade.

HOTOL

The *HOTOL* Launcher (figure 4-2) was conceived as a vehicle optimized solely for the single purpose of significantly reducing launch costs (8).

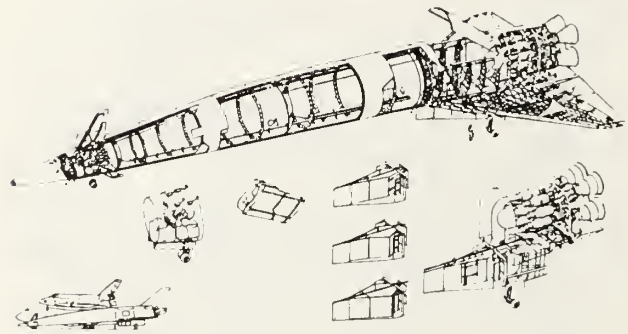

Figure 4-2 : The HOTOL Launcher

HOTOL, which was started in 1984 as a joint project between British Aerospace and Rolls Royce, uses a much more conservative design approach and more available technologies than *NASP* . For example, the original classified RB-545 engine was designed to permit testing of individual sections on the ground first, allowing the engine performance to be fully characterized before installation on the vehicle. This is different to the *NASP* Program which must build and fly a full-up aircraft to test the engine above Mach 8. The *HOTOL* Program was slowed when the UK Government decided to discontinue funding and BAe were asked to look for international support. Unfortunately, these efforts where thwarted by the UK Government's refusal to declassify the RB-545. In September 1990, BAe announced an agreement with the Soviet Ministry of Aviation Industry for joint studies of a pure rocket version - the so-called *"Interim HOTOL"* - launched off the back of the *Antonov-225* aircraft. This, and the original version of *HOTOL*, are primarily unmanned, though "manable,' vehicles and the projected economic and operational performance are approximately the same as the NDV described above.

Sänger

Contrary to the *NASP* and *HOTOL* Programs, Germany believes that the technologies for single-stage-to-orbit will not be available until at least 2010 or later. Therefore, they have embarked on the two-stage-to-orbit design known as *Sänger*, which is currently the reference vehicle configuration in the German National Hypersonic Research Program, and is funded at DM380 million (about $230 million) over five years (figure 4-3) (9).

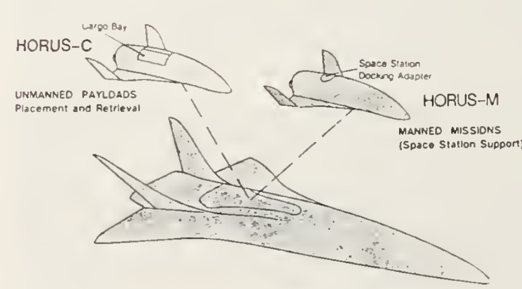

Figure 4-3 : Sänger

Preparations are underway in an effort to "Europeanize" the program for eventual development within ESA. It is hoped that the *Hytex* demonstrator will fly by the turn of the century, and an operational system available by about 2010. *Sänger* consists of a first stage that carries the *Horus* upperstage up to a speed of about Mach 6.5, at which point the upperstage is separated. *Horus* comes in two configurations: the *Horus-M* for manned missions (plus 3.5 tonnes of payload to a *Freedom* orbit) and the *Horus-C* for unmanned cargo missions with a payload capability of about 7.5 tonnes to an equatorial orbit. The estimated launch cost at 50 mission per year is about $15 million per mission.

Should such aero-space plane be successfully built, the first operational systems could be expected to support all the needs of the demonstrator and quite possibly the proposed inter-satellite space power station systems, although, in the latter case, provided one or more alternative launchers are available to ensure failure resilience. For the proposed full-scale SPS, it may require a second or even third generation of ASP that is able to further reduce launch costs, increase flight rates and enhance the payload performance.

4.2 Pure Rocket, Fully Reusable, Single-Stage-To-Orbit Vehicles

Although, as stated in Section 4.1 that vehicles with "airplane-like" characteristics are required for SPSs, this does not necessarily mean such vehicles must *look* like airplanes. As a complement, or possibly even as an alternative to the aero-space plane, are the proposed pure rocket, fully reusable, single-stage-to-orbit launch systems. Such vehicles come in a variety of configurations, including winged, horizontal take-off and landing designs. However, the simplest and best recognized configuration seems to be the vertical take-off and vertical landing configuration, using a linear rocket rocket motor for ascent and for the powered vertical landing.

Such concepts have been proposed in the past, indeed Chrysler proposed just such a vehicle for the Space Shuttle in the late 1960's (10). However, it was quickly recognized that the technical requirements were formidable then, if not impossible. Today, largely as a result of the materials advances being developed by the *NASP* program, it appears that such systems might now be technically feasible. This was the rationale used by the US Strategic Defence Initiative Organization to justify the start-up of the *Single-Stage-To-Orbit* (SSTO) Program, the only funded program of its type at the present time. The *SSTO* (figure 4-4) is also regarded as the first *NASP-Derived Vehicle*. The objectives of the *SSTO* program are to demonstrate that such vehicles can be built and are, initially at least, able to launch payloads in the range 7-10 tonnes into LEO for between $2-10 million per mission at a launch rate of about 50 missions per year.

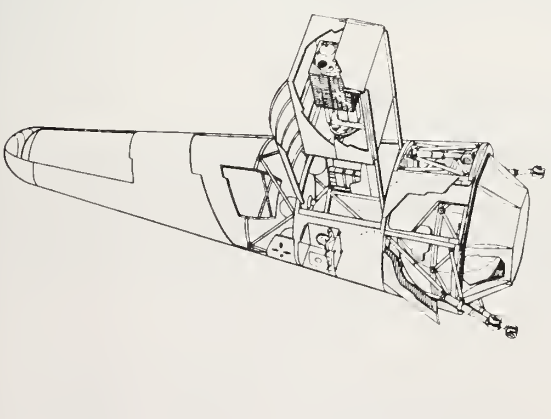

Figure 4-4 : The McDonnell Douglas SSTO Concept

Should *SSTO* vehicles be demonstrated to technically and operationally feasible, then they offer a potential short-cut to achieving the same objectives as air-breathing aero-space planes, although without some of the operational advantages of winged vehicles, especially in the area of return to launch site aborts. Also, another potential drawback is that the take-off mass of the *SSTO* is expected to be as much as 2 times larger than that of a comparable aero-space plane (e.g. about 500 tonnes), although the dry weight is similar. One particular advantage the *SSTO* has over the aero-space plane is the ability to scale the design. For example, the design of an *SSTO* able to launch 10 tonnes can be directly scaled to one that can launch 50 tonnes or more. This could clearly be important for the full-scale SPS development especially if a large *SSTO* could be capable of the'daily' flights that may be necessary.

Another potentially critical advantage of the *SSTO* for the SPS are the environmental impacts. Air-breathing aero-space planes, while burning hydrogen and oxygen (air), also tend to exhaust nitrous oxides and ice crystals at very high altitudes. Although much research has to be performed, potentially, both of these could have detrimental effects on the upper atmosphere in SPS type scenarios where aero-space planes are launched very, very frequently (e.g. several times a day). The SSTO, however, emits only water and because it passes through the upper atmosphere very rapidly, the ice-crystal formation may be much less severe.

4.3 Expendable, Heavy-Lift Launch Vehicles

The need to launch large amounts of mass at low cost per kilogram, at least to establish the SPS in-space infrastructure, has lead many organizations to conclude that expendable, heavy-lift launch vehicles (HLLVs) are required (figure 4-5).

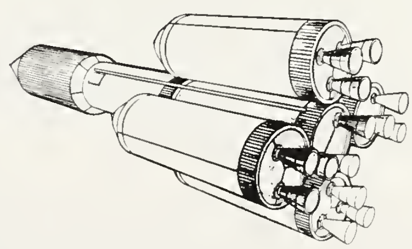

Figure 4-5 : HLLV Concept Proposed by the Synthesis Group

These are essentially one-and-a-half or two-stage vehicles that are capable of placing massive and voluminous payloads in orbit on the top of very large rockets. The rationale used for such boosters is that launching large payloads can reduce the cost per kilogram to orbit, but at the expense of high dedicated launch costs. For example, a launcher that can place 100 tonnes into LEO might be able to reduce the cost per kilogram to $1000, but this will still require a total investment of $100 million for that launch. In addition, because the technologies required to build such vehicle are reasonably well understood, it is believed by some organizations that such a route should be taken. This is the "go with what you know" approach (11).

Unfortunately, while reducing the cost per kilogram might be possible eventually, HLLVs have a number of drawn backs if used to launch all types of payloads. Firstly, testing of HLLVs is likely to be minimal because HLLVs are expendable and, therefore, hardware costs are likely to be high. This is further compounded by the fact that a launcher is expended after every flight and, if a failure occurs, it will be impossible to be absolutely certain what caused that failure. This situation contrasts sharply with boats, cars or planes, they can usually be brought back when problems arise, then modified and re-

tested, thereby allowing the individual characteristics of the vehicle to be fully understood. Secondly, due to the prohibitively high costs of a HLLV test program, the approach being taken is to "engineer" reliability by careful design. Engineering launcher reliability is a very time-consuming and expensive activity because all the critical components (e.g. engines, avionics etc.) must be analysed and tested thoroughly so that the launcher will function properly when assembled for the first time, and it can be made "operational" in as few flights as possible (e.g. *Ariane* and Shuttle only had 4 "test" flights). Unfortunately, even though considerable monies may be invested in engineering reliability, from the critical perspective of the user, *potentially* the launcher may still be prone to failure. No matter how much advanced technology is used, inherently, the HLLV will be a complex *system,* and the only way to prove that such a complex system will work reliably is by flying it many times. Thirdly, when the launcher finally becomes operational, if it has minimal track record and is expensive, then great care will be taken before every mission to ensure the users' very expensive hardware will have the best possible chance of achieving orbit. The owners of a $100 million comsat, or a $500 million reconnaissance satellite, or a $1 billion space station element, are going to spare no effort to ensure that the launcher will work as advertised - *especially* in the case where a failure occurred during the previous launch. Additionally, with expendable rockets like the HLLV, the payload either reaches orbit or is lost - there is no second chance.

The net effect of all this is that the dedicated launch costs will be high, the vehicle will be potentially unreliability, only a few missions can be flown per year, and stand-down times after failures will be long. This is precisely the situation today with all Western launch systems, big or small, while such boosters are used to place a range of payloads in orbit. However, if the HLLV can be restricted to launching just those payloads which are relatively cheap and built in bulk, then the classical situation described above could change. For example, it is possible to envisage a scenario where an aero-space plane-type launcher would be used to launch all 'expensive' payloads of which a few are built, and the HLLV would be used for 'cheap' bulk payloads of which many identical units are built.

In the case of the full-scale SPS, the vast majority of the SPS is equipment that is built in bulk, such as the structures, solar cells and propellants. Thus, it may be possible to launch these payloads on HLLVs at high launch rates, and the occasional failures that occur will not jeopardize continued launches because the impact of such a loss is insignificant. Potentially, the weekly or even daily launching of such HLLVs, could enable a reduction in the dedicated launch costs simply because the large number of vehicles required would permit mass production. Specifically, it would justify the large investment required to allow automatic construction and launch processing needed to reduce costs. Whether it would reduce launch costs to below the $50 per kilogram level, however, would require rather more detailed analysis.

At the present time, the USSR has the only heavy-lift booster, *Energia,* which was actually developed to place 200 tonnes of sand in orbit as a deterrence against possible SDI-type laser systems used offensively, and to launch the *Buran* Space Shuttle. The *Energia* utilizes a robotic construction and checkout process that may well be suitable for SPS type activities. In the US, the former *Advanced Launch System* program was intended to develop the technologies that would permit mass production. However, the push to develop a heavy-lift boosters in the relatively near-term for Space Station *Freedom* has lead to the birth of the *National Launch System* program (12). Evolutionary development of the NLS may eventually permit mass production.

4.4 Electro-Magnetic Launchers (EMLs)

Instead placing large amounts of mass on top of a very large booster like the HLLV, it might be possible to launch much smaller masses but to do this very frequently. One proposal for placing cheap, bulk payloads in orbit is by use of electro-magnetic launchers (EMLs). The EML come in two basic forms; the first is the *rail gun* which generates the armature (projectile) current by direct contact with the rail on which it slides, the second is the *mass driver* where the armature current is achieved by induction. At the present time, the majority of work has been performed on rail gun devices. For example, the Center for Electromagnetics, University of Austin, Texas, USA, has fired a 40g projectile to speeds of up to 12 km/sec, ISL French German Institute, in St. Louis, France, have plans to fire projectiles of 150 g to speeds of about 4km/sec (13). Much of the more recent work was spawned by the US's Strategic Defence Initiative (SDI) program, although there has been interest in the use of mass drivers, in particular, for the launch of materials from the moon for the development of large space colonies and SPS constellations, such as proposed by the Space Studies Institute.

There are numerous advantages to EMLs if used for launching payloads from the Earth. The first is that the operational costs have the potential to be a fraction of that for conventional launchers because they use the cheapest form of energy available : electricity. In addition, the direct environmental impacts are minimal because there is no exhaust. On the negative side, EMLs may only launch relatively small payloads which are subjected to very high 'g' loadings, making them suitable only for launching bulk materials, rather than sophisticated equipment. Additionally, such payloads would either require some form of propulsion system to place them in orbit before collection, or a very large spacecraft would be required to catch these high speed projectiles. More fundamental concerns relate to the technology requirements. At the present time, masses of only a few grams have been accelerated to high speeds as one-off experiments, after which the accelerating system requires significant maintenance for further firings. For the SPS, the ability to launch *several tonnes per day* will be necessary to meet the SPS requirements, and to justify the investment compared with the alternative of the ASP, SSTO or HLLV. For example, if only half the mass required to build an SPS was launched by a EML over a five year period, then the launch rate would need to be about 30 tonnes per day. However, some studies have shown that launch rates per EML of only about 1 tonne per day might be possible (14).

Whether several tonnes per day per EML can be achieved will depend on a considerable investment in research and enabling technologies. Certainly, EMLs hold some promise as a means of reducing the cost to orbit. However, until that research has been performed, it will not be possible to determine the real feasibility and applicability in comparison with rather more conventional alternatives.

4.5 Others Approaches

There are a range of other alternatives for placing large amounts of materials in Earth orbit, including the so-called big dumb boosters (both reusable and expendable) and laser powered launchers. Such systems may play a role in the deployment of full-scale SPS system, however, because only a relatively small amount of basic work is being performed on these concepts, they are not discussed here.

5. Conclusions

From this very general discussion of the requirements for various SPS concepts and after an examination of various future launch system concepts, it would appear that for everything except one-off type demonstration experiments, completely new launch systems are required. In addition, there is no one optimal solution, but a spectrum of optimal solutions. For small-scale operations, such as demonstrating critical technologies and systems in orbit or supporting operational inter-satellite space power stations, vehicles capable of flying to and from orbit regularly, reliably and at low dedicated costs are mandatory. Vehicles that could fit this role include aero-space planes and pure rocket single-stage-to-orbit concepts that are presently being studied. These vehicle are considered the only alternative to ensure that the type of on-demand access to space, for both cargo and people, is attainable. Ideally, in an operational inter-satellite space power station scenario, at least two different vehicles are probably required to ensure failure resilience.

For the proposed full-scale SPS, aero-space planes and SSTOs are also necessary for the launch of crews, logistics and expensive or unique components but, additionally, there is a need to be able to economically launch several 'hundred thousand tonnes' every year. Potentially, there are a number of existing launcher concepts that embody many of the features required to achieve this objective. Most notably, these include expendable, heavy-lift and electro-magnetic launchers. Certainly, such system only become attractive for the frequent launching of relatively cheap, bulk materials for the SPS and the in-space infrastructure required to support the SPS construction.

In conclusion, the first step in determining the feasibility of any type of SPS is to be able to get into space as required by the needs of research. Such a capability does not exist today, and until it does, the SPS will remain just an idea that cannot be realized.

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B6.3 The plasma launchers for SPS

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ABSTRACT

The possibility of creation of the terrestrial electric accelerators for launchings on orbit the SPS components is discussed.The accelerator that uses for the projectile acceleration the anomalous plasma pressure is put forward.It is shown that such an accelerator has essential advantages before an accelerator that uses the Ampere force.

RESUME

On discute la possibilité de créer un accélérateur électrique sur la terre pour la mise en orbite des composants du SPS. On propose d'utiliser la pression anormale du plasma comme source d'accélération. Un tel accélérateur a des avantages essentiels sur l'accélérateur utilisant les forces d'Ampère.

Introduction

It would require not less than a thousand launchings of such a launcher as soviet "Energia"("Energy") to deliver on geosynchronous orbit the components of only one SPS with the firm power 5-10 million kilowatts and the total mass 20-50 thousand tons.The launch cost would be 80-200 billion dollars and may be recover at the expence of the electric energy produced by the SPS in only about a hundred years.

Taking into account the ecological problems that the frequent tremendous rocket launchings bear,the rocket launchers for SPS must be treated as non-perspective.It is very likely that not the rockets but the terrestrial electric accelerators,which advantages before the rockets have been yet noted by C.E.Cziolkovsky[1],will give a solution of the problem.

To deliver something in space it needs to supply this something with the first cosmic velocity plus the potential energy that depends on orbit altitude,or in total with the mechanical energy about $3{,}5\cdot10^7$ J/kg.It means that at commercial cost of electric energy 2 cent/kWh the cost of delivering in space may be only 20 cent/kg instead of 1000 dol/kg.If a cheap technology for projectile acceleration by electric energy would be available the launchings of the components of future SPS would be cost only about a ten million dollars.

The low cost of electric energy produced by the nowaday electric power stations in comparison with the cost of mechanical energy that the rocket engines give to satellites is the main argument for the space transport electrification.

"But how the electric energy must be transformed into the mechanical energy?- Cziolkovsky asked[1].-No electric engines because of their mass are useful here..."

Electromagnetic Launchers

Since the final projectile velocity is determined so accelerator parameters depend mainly on the accelerator length. The values of accelerations and powers to reach at the efficiency =1 the velocity 10 km/s by a 10-ton projectile in accelerators of different lengths are shown in Fig.1.

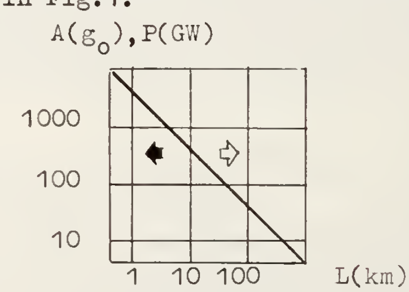

Fig.1

Accelerations and powers as accelerator length functions

The low length limit is conditioned by the projectile strength limit,the upper one is corresponding to the accelerations that allow people to start in space by

direct launchings. C.E.Cziolkovsky thought about the lengthy accelerators and relatively smallaccelerations and powers(the light arrow in Fig.1). But practically the electromagnetic acceleration technology development began with the extremly high accelerations and powers (black arrow in Fig.1).

As early as before the World War II not a few proposals were put forward about the linear electric accelerators, of inductive type mainly. But for supplying such an accelerator with energy the electric power station(power 5-10 GW or more) must contain the transformer guaranteeing the smooth change of current frequency from approximately 100 s^{-1} till 10 000 s^{-1}. Such a transformer the nowaday electrical engineering does not know.

The absence of the frequency transformers and the inconvenience of the lengthy accelerator(that yet must be made!) forced the investigators to build up the energy stores and the megaampere current generators with the impulse power comparable with the total power of all electric stations of such countries as USSR or USA. In Australia, then in USA the stores-generators were build up and used with the short railguns that is with the one-turn coil a part of which is the travelling crosspiece-armature.

The first experiments were done with solid metal armatures, the electric current flowed through the sliding contacts between the armature and the rails(Fig.2a). It has been found out that the sliding contacts limit the armature velocity at the level of 1-3 km/s. This limitation brought the investigators to such a mode of railgun function at which the armature forms from the arc plasma(Fig.2b). The Ampere force influenced on the plasma armature, and the latter on the back(dielectric) wall of a projectile or the charger that contained a projectile.

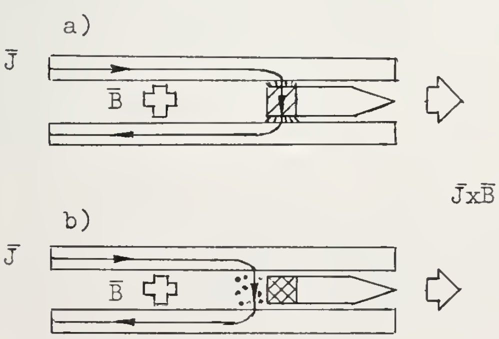

Fig.2

The electromagnetic rail accelerators:
a)with metal armature,
b)with plasma armature.
$\bar{J}$-current, $\bar{B}$-magnetic induction

With help of the rail accelerators with plasma armature the most impressing results in the field of massive body acceleration have been achieved. At first the polycarbonate cube of mass 3 g was accelerated till velocity 5,5 km/s in the railgun of length 2 m with the square cross section channel of calibre 12,7 mm, then the united research group from Los Alamos and Livermor(USA) obtained the instantaneous X-ray photo of the tantalum disk accelerated in the polycarbonate charger till 11 km/s[2].

Deficiency of the Ampere accelerator with plasma armature

This type of accelerator is now the best one to realize the massive body acceleration. But it is not free of disadvantages, among them the main is the danger of parasitic electric discharges.

As a projectile is travelling along the rails, the discharge circuit inductance is increasing and because the electric breakdown places correspond to minimum inductance the parasitic electric breakdown possibility is increasing too. The electric discharges behind a projectile, near the beginning of the rails, not only decrease the electric current in the plasma armature and consequently the accelerating force but lead to rail destruction and destroying of the accelerator itself. Taking into account the tremendous power of the full-scale acceleration system such a short circuit at the beginning of the rails must be considered as inadmissible.

That is why the search of new electric accelerators should be continued.

Anomalous plasma pressure

In smooth plasma at complete(single) ionisation it ought to take into consideration two pressures: the kinetic pressure of electrons and ions

$$p=n(T_e+T_i) \qquad (1)$$

and the magnetic pressure

$$p=B^2/2\mu_0, \qquad (2)$$

where n-plasma density, T_e and T_i-electron and ion temperatures in energy units, B-magnetic induction, μ_0-the magnetic permeability of vacuum.

In turbulent plasma with Langmuir fluctuations it becomes essential the pressure of the turbulent electric fields:

$$p_E^T=\frac{\varepsilon_0}{2}\langle (E^T)^2\rangle , \qquad (3)$$

where ε_0-the electric permeability of vacuum, $\langle (E^T)^2\rangle$ -the average square of

Conclusion

The future SPS components maybe after all will launch by the lengthy electric accelelator such as C.E.Cziolkovsky have written about(Fig.1,the right side).

But it is more likely that the electric gun lengths will limit by 1-10 km.It means that the necessary traction density(the pressure on the back wall of a projectile) will be about 10-100 MPa.In this case the accelerator that uses the anomalous plasma pressure may be the best solution of the direct launch problem.

It must not be forgotten of course that besides the accelerator itself a number of other and not less difficult problems must be solved,such as the energy accumulator,the form of projectile that must allow to make projectile's way through atmosphere and launch a projectile at the expense of the aerodynamic quality on the Earth orbit,the towing of a projectile towards geosynchronous orbit and so on.

But if the electric launching technology is elaborated,supplying the power of only one large-scale electric power station(such as Krasnoiarsk station in Siberia) it will be possible every 5 minutes to deliver in space a 10-ton body,and in 10 years to launch on orbit so much material that it would be possible to build 100 SPS.

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B6.4 A comparison of a conventional launch system vs. externally supplied vehicles for installation and maintenance of solar power satellites

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ABSTRACT

The paper analyses two principal approaches for the transportation system to support the operational phase of an SPS scenario that foresees the continued installation of two 10 GW stations p.a. equivalent to 150,000 Mg payload p.a..

One concept consists of conventional SSTO vehicles, the structure of which is left in orbit and used to build-up the structure of SPS. As an alternative concept an externally supplied vehicle is being considered , the required power is being supplied by laser from ground.

A comparison of these two approaches showed, that the conventional launch system is preferable, because it is technically feasible and simpler in development, and no significant impact to atmosphere can be seen.

RESUME

Le document analyse les deux approches principales du systéme de transport, support de la phase opérationnelle d'un scénario de SPS qui prévoit l'installation annuelle, en continu, de deux stations de 10 GW équivalent à une charge payante de 150.000 Mg.

Un des concepts consiste en l'utilisation de véhicules conventionnels type SSTO, don't la structure, laissée en orbite, est intégrée à celle du SPS. Dans l'autre concept, le véhicule a une alimentation extérieure, l'énergie nécessaire étant fournie par laser depuis le sol.

La comparaison entre ces deux approches a montré que le système conventionnel était préférable car techniquement faisable, plus simple à développer, et sans influence notable sur l'atmosphère.

Introduction

In order to realize Power from Space several concepts concerning transportation scenario have been proposed. The Global Solar Energy Concept GSEK [1], it is the reference concept for this paper, foresees the continuing installation of two 10 GW power stations p.a. equivalent to 150,000 Mg payload p.a. from 2025. For these very high transportation requirements a suitable fleet of HLLVs must be provided.

For development and testing the concept is being scheduled into three main phases:

1993 - 2005 Experimental-Demonstration Phase

2006 - 2018 Pilotphase

from 2018 Operational Phase

As the three phases are very different in regard of launch rates and payload masses, they will be discussed separately. In particular the critical aspects concerning technology, logistics, economics and ecology will be shown.

While the experimental-demonstration phase technology and reliability shall be tested in a laboratory scale. This phase finishs in building-up an 1 MW-Demonstration station.

For these projects no vast problems concerning transport Earth - LEO can be expected. Conventional launch systems like Ariane IV, V or STS are fully sufficient for cargo-transport, for the personnel-transport Space Shuttle or ArianeV + Hermes are fully sufficient, too.

At the beginning of the pilotphase an orbital spaceport and a fleet of OTVs shall be installed. This phase finishs in building-up an 1 GW Pilot-powerstation. Fig. 1 shows that about 3200 Mg payload p.a. is to be transported in the end of the pilotphase. Assuming an HLLV with a payload capacity of 50 Mg the cargo transport demands 60 - 70 LpA.

This scenario requires progressive technology for transportation systems and a special view to the environmental impacts. However, the transportation scenario of this phase is feasible using basically conventional technologies for construction of the Heavy-lift vehicle.

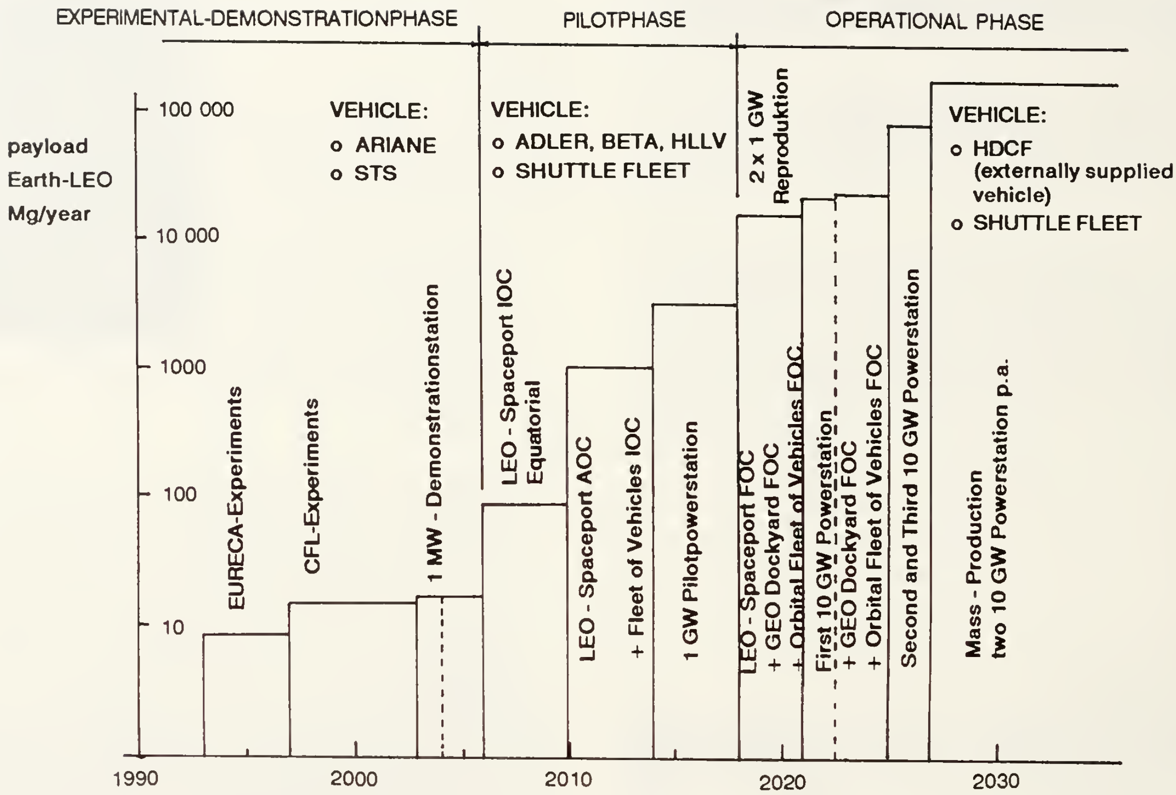

Fig. 1 Time Schedule of GSEK

The personnel launch vehicle might be an advanced shuttle system like Space Shuttle II or Saenger. Problems concerning logistics cannot be expected. The relevant problems as such arise in the operational phase. Fig. 1 shows the structure of this phase in connection with the payload to be transported.

The time schedule for installation of the orbital infrastructure and demonstration stations seems to be sensible: the parallel installation of infrastructure and first powerstations benefits a flexible reaction to not foreseen changes, respectively fitting of the infrastrucutre.

For further considerations concerning transportation systems the mass production phase from 2018 is being regarded as reference, because then the highest emergence of payloads, leading to about 4000 LpA, will occur.

In addition to the technological problems the ecological aspects are especially significante. Moreover, economics and logistic problems will be considered.

In order to provide the cargo transport Earth-LEO two principial approaches for the transportation system are being analysed.

One concept consists of SSTO vehicles with fully reusable engine and avionics modules. These vehicles are equipped with conventional engines, the propellant consists of LH_2/LOX. The structure (tanks etc.) is left in orbit and used to build-up the structure of the SPS.

As an alternative concept an externally supplied vehicle is being considered. The required power is being supplied by laser from ground by which the stabilizing medium in the combustion chamber of the engine is heated up. The structure of this vehicle is also used to build-up the structure of SPS.

Conventional Launch System

In order to minimize the expenditure for operations the HLLVs must be optimized in respect to size and construction, propellants and propulsion system, reusability and reliability. One approach consists of a conventional vehicle, the structure of which is left in orbit and used to build-up the structure of SPS.

Sizing these vehicles lead to a payload capacity of about 50 Mg, much larger vehicles are not suitable for using their structure to build-up SPS [1]. In addition, problems regarding flight stability can be identified, and the costs for development would probably be much higher than for a 50 Mg vehicle.

On the other hand smaller vehicles are not efficient for the high transportation requirements: Assuming a vehicle with a payload capacity of 20 Mg the launch rate increases to about 10,000 LpA equivalent to 30 launches per day! Whether the structure of these vehicles can be used for build-up an SPS seems to been doubtfully at least.

On principle, the highest efficiency will bé obtained by consequently design to cost: the payload is to be standardisized and the vehicle has to be designed to payload.

As the structure is used as "secondary payload" in orbit, an SSTO-vehicle is to be preferred. The engine/avionics module is to be constructed as fully reusable, ballistic reentry system.

The propellant consists of LH_2/LOX, all other propellant combinations lead, due to lower specific impulses, to considerable higher pollution.

In order to maximize the efficiency, a rocket engine is to be developed, that provides the (staged) combustion in the ratio 1:8 (LH_2 : LOX). Assuming a specific impulse of 450 s and a structure ratio of 5% (engine/avionics modul) lead to a payload fraction of about 6% for launch near equator. This results in a total propellant mass p.a. of about $2.375 \cdot 10^6$ Mg, subdivided in $264 \cdot 10^3$ Mg LH_2 and $2.11 \cdot 10^6$ Mg LOX.

Energy Demand and Cost

The energy required for production of LH_2 is divided in energy for electrolysis and energy for iiquefaction.

$$E_{res} = E_{elect.} \cdot E_{liq.} \qquad (1)$$

$$LH_2: \frac{E}{m} = 56\ KWhe/kg + 13\ KWhe/kg \quad [4]$$

$$\frac{E}{m} = 69\ KWhe/kg$$

The energy for liquefaction of oxygen is being assumed to

$$LOX: \frac{E}{m} = 5\ KWhe/kg$$

Thus, the total energy demand p.a. for allocation of propellant is given to

$$E_{res/a} = \frac{E}{m}(LH_2) \cdot \frac{m}{a}(LH_2) + \frac{E}{m}(LOX) \cdot \frac{m}{a}(LOX) \qquad (2)$$

$$E_{res/a} = 18.2\ TWhe + 10.5\ TWhe$$

$$E_{res/a} = 28{,}7\ TWhe\ (= 28{,}7 \cdot 10^{12} Whe)$$

Assuming a capacity of factories for electrolysis and liquefaction of 8000 h/a the required net power is given to

$$P_{net} \approx 3.6\ GW$$

equivalent to 36% of one 10 GW-SPS. Hence, this seems to be justifiable from economic view.

The specific cost for allocation of LH_2 is given by the sum of costs for electrolysis, liquefaction and storage multiplied with the factor of the evaporation rates:

$$LH_2: K = (K_{electr.} + K_{liq.} + K_{stor.}) \cdot$$

$$\cdot\ (1 - \Delta m_{transport} - \Delta m_{storage} - \sum \Delta m_{transfuse})^{-1} \qquad (3)$$

costs:

$$K_{electrolysis} \approx \$\ 3.70/kg \quad [4]$$

$$K_{liquefaction} \approx \$\ 1.30/kg \quad [4]$$

$$K_{storage} \approx \$\ 0.30/(kg \cdot month)$$

evaporation rates:

transfuse, fill-in $\Delta m \approx 8\%$ [4]

factory - liquefaction - storage - lorry - rocket

$\Rightarrow \Delta m_{transfuse} \approx 32\%$

storage, transport by ship $\Delta m \approx 0{,}1\%/d$ [4]

30 d storage : $\Delta m_{storage} \approx 3\%$

The production of propellants far from space center is not economical because two more transfuses (~ 16 %) and transport (0,1 %/d) would yield a considerable increased evaporation rate and the transport would have to be paid. In addition, the factories are technically simple. So the production near space center seems not to be a problem.

Total cost for allocation of LH_2:

$$K_{tot}(LH_2) \approx \$\ 8{,}15/kg$$

All cost declarations are related to electrical energy cost of \$ 0.07/KWhe with amortization of 30 years by tax on real estate of 4% [4].

Assuming the cost for allocation of LOX with \$ the total cost p.a. for allocation of propellants is given to:

$$K_{tot}/a = K(LH_2) \cdot \frac{m}{a}(LH_2) + K(LOX) \cdot \frac{m}{a}(LOX) \qquad (4)$$

$$K_{tot}/a = \$\ 2.15\ billion + \$\ 3.165\ billion \approx \$\ 5.3\ billion$$

The annual cost for production of propellant is in the order of the receipt of one 10 GW SPS assuming an electrical energy price of \$ 0.07 / KWhe.

Cost for Transport

The total life receipt of one 10 GW SPS is in the order of \$ 200 billion. The payload to be transported is 75000 for one 10 GW-SPS according to the reference scenario. From economical view the maximum cost for transport Earth - GEO might be 25 % of the total life receipt, leading to specific transport costs of about \$650/kg.

Assuming future operation capability and seriell production of standardisized vehicle this seems to be attainable.

Externally Supplied Vehicle

Because of the environmental impact of conventional launch systems the concept of an externally supplied vehicle HDCF (Heavy Duty Cargo Freighter) is being proposed. This launch system is equipped with a laser-thermical propulsion system, the required power is being supplied by laser from ground or space. For conversion of energy into thrust an environmentally compatible stabilizing medium is heated up in the combustion chamber of the engine. As the thrust depends no longer on the combustion enthalpy, very great specific impulses are theoretically possible.

As a general, great specific impulses yield lower lift-off weights, leading to lower massflow rates and, consequently, to reduced pollutant masses emitted to atmosphere .

However, the great specific impulses are restricted due to the quadratically increasing combustion chamber temperature (Equation of St. Venant and Wantzel). With magnetic confinement of the jet temperatures of up to some 10,000 deg Celsius may be handled. This assumption seems to be very optimistically and should be analysed more detailed. The high combustion temperature is, in addition to the technology of high power laser, the most significant problem of the requested configuration.

the specific impulse is in inverse ratio to the square root of the molecular mass, the density of the (liquid) stabilizing medium determines size of vehicles.

In respect to type an amount of pollutant, technical suitability and availability, hydrogen (H_2), helium (He), nitrogen (N_2), oxygen (O_2) and argon (Ar) are being selected for analysis.

As the molecular mass should be as small as possible, heavier elements or chemical compounds do not come into consideration. Tab. 1 shows the characteristic data of the selected materials.

Assuming the prescribed scenario with a launch vehicle of 50 Mg payload capacity (SSTO) following approach is being made:

payload: $m_{PL} = 50\ Mg$

burnout mass: $m_b = 3 \cdot m_{PL} = 150\ Mg$

the launch mass is given by the basic equation of rockets (Ziolkovski)

$$m_o = m_b \cdot \exp(\frac{\Delta V}{I_{sp} \cdot g_o}) \tag{5}$$

with

$\Delta v = 9{,}5$ km/s (LEO)

	H_2	He	N_2	O_2	Ar
M [g/mol]	2	4	28	32	40
κ [-]	1.4	1.66	1.4	1.4	1.66
$\overline{Cp}$ $\left[\frac{KJ}{kg\ \ K}\right]$	1.28	0.931	1.30	1.31	0.933
T_B [deg C]	-252.8	-268.9	-195.8	-183.0	-185.9

Tab. 1 characteristic data of various stabilizing mediums

M Molecular Mass

κ Isentropic Exponent

$\overline{Cp}$ Mean Specific Heat Capacity

T_B Boiling Temperature

A power estimation resulted in an upper payload limit of approximately 50 Mg. In this case the required laser power is in the order of some 10 GWs, thus a dimension, the handling of which is presupposed by the SPS concept.

In comparison, a conventional launch system of the same magnitude (50 Mg PL/SSTO) and a payload fraction of 5 % produces approximately 30 GW.

In addition to the technological problems another critical aspect for an externally supplied vehicle is the selection of the stabilizing medium: on the one hand the stabilizing medium is the emitted pollutant (in type and amount), on the other hand the stabilizing medium determines configuration and engine-type of the vehicle:

The specific impulse I_{sp} depends on the stabilizing medium and determines the required power and the temperature of the combustion chamber and, consequently, the entire amount of stabilizing medium. The lift-off thrust is at least equivalent to the gravity force of the launch mass:

$$F_E = m_o \cdot g \tag{6}$$

the mass flow rate is given by

$$\frac{dm}{dt} = F_E/(I_{Sp} \cdot g) \tag{7}$$

The temperature of combustion chamber is implicit given by Equation of St. Venant and Wantzel:

$$I_{Sp} \cdot g = c_e = \sqrt{\left(\frac{2\kappa}{\kappa - 1} \cdot \frac{T_c}{M} \cdot R\right) \cdot \left(1 - \frac{p_e}{p_c}\right)^{\frac{\kappa - 1}{\kappa}}} \tag{8}$$

with

c_e	exhaust velocity
R	universal gas constant
p_c/p_e	ratio of expansion

The ratio of expansion (ground) is being appointed to

$(p_c/p_e)^0 = 200$

a greater value seems not to be possible.

The power required for heating-up of stabilizing mediums is given to

$$P_{(i)} = \frac{dm}{dt} \cdot \Delta T_{(i)} \cdot \bar{c}_{p(i)} \tag{9}$$

$\bar{c}_p =$ mean specific heat capacity

Hydrogen (H_2)

From technical view hydrogen is the most favourable attempt (tab. 2). The technology of combustion chambers for temperature of about 4000 K is already state of technique, magnetic confinement of the jet is not necessary. Hence, the structure mass considerably decreases and the operational risks will be as small as possible. The production of LH_2 is technically simple and inexpensive, the resources are inexhaustible. However , the emittance of molecular and/or dissociated hydrogen seems to be problematically.

conceivable reactions:

$H_2 + O_3 \Rightarrow H_2O + O_2 + E\uparrow$

$H_2 + \frac{1}{2}O_2 \Rightarrow H_2O + E\uparrow$

$2H^+ + O^{--} \Rightarrow H_2O$

The emitted amount of hydrogen is 3-4 times higher than for a conventional launch system. Due to reaction of hydrogen and oxygen/ozone the amount of water in atmosphere is 3-4 times higher, too. Thus, a chemical propulsion system (LH_2/LOX) would be preferable.

Helium (He)

Helium is quite suitable from technical view, the required power of about 4 GW is more realistically than for oxygen, nitrogen and argon. The temperature of the combustion chamber of approximately 11000 K might be handled, but magnetic confinement of the jet seems to be necessary. The impact to atmosphere seems to be not critical: inert gases only react at very high pressure, at atmospheric pressure they are absolutely inert.

However, the production of liquid helium is certainly very expensive. Especially expenditure for liquefaction is very high, because the boiling point of helium is at 4.25 K (1013 mbar). Beside this, the resources of helium are strongly limited (helium : 0,0005 % Vol. of atmosphere).

Due to economics and scarcity of resources, helium seems not to be suitable for stabilizing medium.

Nitrogen (N_2)

The technical handling of nitrogen is critical, the desired specific impulse of 1000s probably cannot be maintained. Assuming I_{Sp} = 500s, a combustion chamber temperature of 15000 K and required power of about 21 GW are expected. However, for optimistical assessment of technology the utilization of nitrogen might be feasible.

The production of liquid nitrogen is technically simple and inexpensive, the resources are inexhaustible.

After expansion there are still jet temperatures of several 1000 K, thus nitrogen will react with oxygen/ozone to nitroxyde (NOX).

The impact to atmosphere of nytroxydes in this amount is to be analysed more detailed. However, a noticeable negative impact is to be regarded as sure.

	H_2	He	N_2		O_2			Ar		
I_{sp} s	1000	1000	500	1000	500	700	1000	500	700	1000
GLOW kg	390	390	1000	390	1000	580	390	1000	580	390
T_c deg C	3990	10200	14000	55800	16000	31300	63850	25500	50000	102200
P GW	2	3.7	36.4	28	42	34	32.6	24	27	37.2

Tab. 2 technical data of vehicles for various stabilizing mediums

I_{sp}	Specific Impulse
GLOW	Gross Lift Off Weight
T_c	Temperature in Combustion Chamber
P	Required Power

Oxygen (O_2)

Enormous technological problems are expected if oxygen is used as stabilizing medium.

However, in comparison to the other mediums the technical complexity is in the medium range. As neither hydrogen nor helium nor nitrogen are suitable, oxygen is - on condition of the concepts principle feasibility - the most likely handable stabilizing medium. Magnetic confinement of the jet is indispensible, because dissociated oxygen is extremely aggressive. Thus, it would destroy the hardware of the engine.

An impact to atmosphere cannot be identified, but a detailed analysis is requisite for every case.

Due to emittance of oxygene into ozone cycle even a "curing effect" is conceivable (hypothetically!). The resources are inexhaustible (21% Vol. atmosphere, 89% water), liquefaction is technically simple and inexpensive.

Argon (Ar)

The handling of argon is most critical, the desired specific impulse of 1000s can surely not be maintained. Reducing to I_{sp} = 500s leads to a combustion chamber temperature of about 25,000 K and power to be supplied of 26 GW. It is questionable, whether the technology can be provided at all.

If necessary, smaller vehicles or booster support up to 10 km altitude must be analysed.

The impact to environment seems to be uncriticeal, according to the causals of helium.

Production and liquefaction of argon is technically simple and inexpensive, the resources are sufficient (argon: 0.93% Vol. of atmosphere).

Appraisal

The concept of an externally supplied vehicle is being founded by reduced environmental load and increased payload fraction of up to 25%. Thus, analyzing only technical feasibility would not be sensible because conventional systems are remarkable easier in development and operations. Nevertheless feasibility on justifiable cost must be provided.

Environmental compatibility and technology are strongly connected: if high specific impulses are not achievable the mass flow rate and, consequently, the amount of pollutant increases.

As analysis has shown, only oxygen or argon are suitable for an externally supplied vehicle. However, these concepts will lead to nearly unsurmountable technical problems.

Economic benefits due to higher payload fraction are not expected because the expenditure for development is substantially higher and the operational costs are, due to extensiv ground stations, not less than the costs for a conventional system.

A rough estimation has shown, that for the reference scenario a conventional launch system yields no significant ozone change [7]. Thus, a conventional launch system is, subject to detailed atmosphere-chemical analysis, to be preferred.

Infrastructure and Logistics

Due to its magnitude and complexity the considered scenario is to be realized in an international framework. The decisions concerning launch base and infrastructure will be caused by policy more than by technical aspects. From present view only some technical requirements can be placed.

Assuming 11 launches per day 7-8 launch bases are required in minimum. The personnel transport may be separated from cargo transport.

Due to energetic aspects launch bases near equator are absolutely necessary for cargo transport. It should be analysed, whether artificial islands in international waters are suitable and to be built to justifiable costs.

If the PLV is capable of cruise, launch- and landing bases are nearly arbitrary.

The most relevant aspect of logistics is the information transfer betweeen the international partners, because a complex system like this needs a very carefully planned coordination.

It is avisable to develop all systems in an international framework to get a standardization and avoid double developments. The production of technical components , payloads and propellants might be at place in national programmes.

Summary

After experimental- and pilotphase the problems as such occur in the operational phase. The technological problems are mainly in development, production and operation of the proposed HDCF. Particulary the energy-transfer by laser and the extremely high temperature of combustion chamber lead to nearly unsurmountable problems.

Due to environmental compatibility the selection of the stabilizing medium is of special significance. Analysis showed that only oxygen or argon seems to be suitable for the externally supplied vehicle. However, these stabilizing medium lead to highest requirements to technology.

More favourable seems to be the utilization of an conventional launch system equipped with chemical propulsion system. The required technology bases on existing systems like Energia, problems concerning environment are not expected.

If there will be no other findings concerning environmental compatibility this launch system is to be preferred.

An other additional issue is the extremely high launch rate of approximately 4000 launches p.a.. However, in comparison to the other problems in connection with the discussed transportation scenario this seems not to be an unsurmountable problem.

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Klima in Gefahr
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B6.5 Earth based microwave power beaming to interorbital (LEO to and from HEO and GEO) electrically propelled transport vehicles

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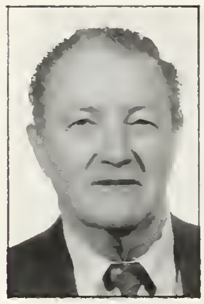
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ABSTRACT

An equatorial internationally based transportation system that can transport large masses of material from low earth orbit (LEO) to geosynchronous earth orbit (GEO) at low cost has been recognized as essential to the deployment of the Solar Power Satellite System (SPS). This paper presents an all-electronic LEO to GEO and return transportation system (Ref. 1) that combines the high specific impulse of the ion thruster with beamed microwave power. The microwave power sources are placed at strategic locations around the earth at the equator.

RESUME

Un système de transport spatial international capable de transférer des masses importantes d'orbite basse (LEO) en orbite géostationnaire (GEO) à faible coût est indispensable au déploiement du SPS. La communication présente un système combinant propulsion ionique et source d'énergie à faisceau de microondes. Les sources microondes sont placées à des emplacements stratégiques sur l'équateur.

1.0 INTRODUCTION

Two well advanced technologies, those of the electric ion thruster and beamed power transmission, can be combined to provide the impulse required to raise and or lower the altitude of transport vehicles. This all-electronic propulsion subsystem can be implemented most simply where the operation is in the equatorial plane. Ground based transmitters that steer their power beams through large angles from easterly through zenith to westerly elevations as well as through very small angles north and south of zenith can be of the simplest form. These, in simplest form, are each constituted by multiples of a phase-locked magnetron transmitting through a single linear waveguide emitting its in-phase rf power uniformly through slots along the length of the radiating waveguide. By controlling the relative phase of the microwave output of such magnetron with respect to its neighbors, a coherent phase front can be launched from a large array on the equator (a) over large elevation angles about the long (north-south) axes of the radiating waveguides, and (b) over small angles normal to those axes.

The emitted rf power will be coherent so as to focus the power beam on a compatibly-oriented linearly polarized rectenna on the Interorbital Transport Vehicles (IOTV's) as they pass in orbit over the Ground Based Transmitters (GBT's). The transmitters on the ground and the rectennas on orbit are all in the equatorial plane thereby making full utilization of each GBT every orbital revolution.

2.0 BRIEF DESCRIPTION

Mechanization of such an all-electronic transportation capability from LEO to GEO and return includes a ground-based high power source feeding a large microwave transmitting antenna that beams power to a large on-orbit receiving and rectifying antenna (RECTENNA) which supplies power to the electric thrusters of an Interorbital Transfer Vehicle (IOTV). It combines the high specific impulse of the electric thrusters with the recently developed light weight radiation-hard rectenna.

3.0 PAYOFF OR VALUE

The value of the "IDEA" is that, as a power source for electric thrusters, it makes possible an electric transportation system from LEO to GEO and return. It thereby greatly reduces the dependency of an IOTV upon conventional chemical propulsion. More specifically, the microwave powered IOTV will reduce, by a factor of 10 or more, the amount and associated transportation cost of propellant that must otherwise be transported

from Earth to GEO for use in a chemically propelled IOTV designed for transportation to GEO and return to LEO.

The microwave-powered IOTV would be used to transport equipment assemblies of the SPS (that have come from the earth) from LEO to GEO as well as to return appropriate equipment to LEO as may be required.

Another payoff, due to the low vehicle acceleration provided by electric thrusters, is the greatly reduced vehicle structural mass and the greatly improved ability to transport large fragile structures. Furthermore, on its return trip to LEO the microwave powered IOTV does not subject itself and its payload to the high deceleration and temperature environments characteristic of aerobraked concepts.

Because of the very low 1 Kg/Kw specific mass of the RECTENNA, lower by a factor of 10 than either photovoltaic or nuclear sources, unprecedented high accelerations for an electrically propelled vehicle are possible. Transit times from LEO to GEO in a mature system range from 30 days for a vehicle with 50% payload, to less than 10 days for an express, small payload mission.

Modularity and repetitive use of proven components in both the ground and space segments (magnetrons and diodes) assure high reliability and long life. Modularity also makes the expansion of the system straightforward and economical.

4.0 PERFORMANCE CHARACTERISTICS

The microwave-powered IOTV routinely transports payload from LEO to HEO or GEO and returns to LEO.

The baseline system to be described here can deliver to GEO 120 metric tons of payload per year. A mature system can deliver as much as 30,000 metric tons per year.

The baseline system can transfer a Kg of payload from LEO to GEO by expending 4,000 KwH of 60 Hz earth-generated energy. A mature system using larger IOTVs would reduce this to 800 KwH per Kg of payload.

5.0 OTHER ENABLING TECHNOLOGIES OR SYSTEMS

Other items needed to make the Earth-based microwave power beaming in the IOTV application viable include the availability of ground based Energy Sources, the on-orbit Electric Thrusters, mission-appropriate Radiation Protection, and Large Space Structures.

Energy Sources are large and conventional, needing no development, but need to be made available at to-be-selected ground locations.

Electric Thrusters are in an advanced state of development and have been used in space applications. They need to continue development with emphasis on an efficient interface with the IOTV RECTENNA.

Protection or otherwise hardening of the IOTV's and payloads will be necessary due to their exposure to natural radiation encountered during the long Van Allen belt transit times and the stay time at intermediate altitudes within the belt as well as at GEO.

Large Space Structures' technologies being developed for other applications must include consideration of requirements unique to the IOTV application.

6.0 RELATION TO MAJOR MISSION OBJECTIVES

Mission objectives center around "Transporting SPS payloads to operationally assigned segments at GEO".

The "IDEA" of a HEO staging region and an operational region at GEO, with traffic of cargo from and to LEO facilitated by the microwave powered IOTV, provides a basis upon which additional power beaming and equipment transportation options may be developed.

7.0 EXPANSION ON THE PREVIOUSLY INTRODUCED TOPICS

The operational and performance characteristics of the all-electronic transportation system that microwave power beaming makes possible will now be examined with the aid of Figures 1 through 4.

Figure 1 describes the main features of the system and gives the design parameters of the baseline, or reference system, which has been studied for transport between LEO and GEO. It consists of a high-powered ground based transmitter that generates a tightly focussed microwave beam that impinges upon and is absorbed by a rectifying antenna (Rectenna) on the IOTV. The 20 megawatts of DC output from the Rectenna energizes, typically, several hundred ion thrusters operating at a high (4000 sec) specific impulse. As shown in Figure 4, the baseline design is capable of placing a 50% payload (equivalent to 60,000 Kg) into GEO in about 100 days. Moreover, the system can be expanded to place the same payload into GEO in 25 to 30 days.

Figure 2 shows the expanded or "mature" system as seen from a position high above the North pole. A mature system has four IOTVs and has four land bases on the equator. The IOTVs travel to GEO in outward-spiralling orbits in the equatorial plane. Both the GBT's and the IOTV's must be located in the equatorial plane so that the IOTVs will make contact with each of the microwave beams on each successive orbit. The electronically steerable beam that is emitted from each transmitter tracks an IOTV for a total angle of 90 degrees and then "hands over" the IOTV to another beam. The relatively short duration of the contact time between the beam and the vehicle in orbits close to the earth has been taken into account in computing the total elapsed time to reach GEO.

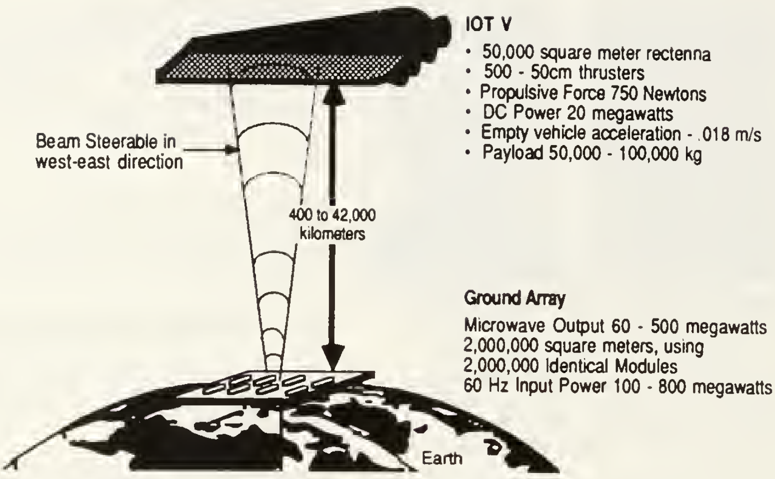

FIGURE 1. DIAGRAM OF THE BEAM POWERED LEO TO HEO TRANSPORATION SYSTEM

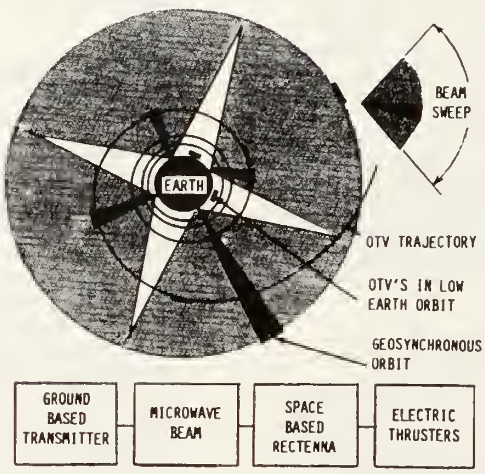

FIGURE 2. THE MATURE BEAM POWERED TRANSPORTATION SYSTEM AS SEEN FROM A POSITION OVER THE NORTH POLE

Figure 3 shows the possible location of the four high powered transmitters (black circles) on the Earth's surface, including Jarvis Island which occupies a strategically located region within a fraction of a degree of the equator in the middle of the Pacific Ocean.

8.0 PREVIOUS HISTORY

The "IDEA" has been proposed before (Refs. 1,4). Subsequently it was amplified upon and presented (Ref 5) at a symposium sponsored by the NASA, AIAA, Lunar and Planetary Institute, American Geophysical Union, American Nuclear Society, American Society of Civil Engineers, Space Studies Institute, and the National Space Society. Other similar forums have been addressed (Ref 2). It is intended to be reported-upon most completely in Reference 6. Until recently, the concept represented by this "IDEA" was generally regarded as being unrealistic for immediate application.

What has changed is the introduction of the SEI with its emphasis on "long-term- commitment of resources, both financial and human, and of national will." We believe that the equatorially-based Microwave Power Beaming "IDEA" applied as an earth-based source of on-orbit power for interorbital electric propulsion, is realistic for missions where large payloads are to be transported on an international basis from LEO to HEO and particularly to GEO. Such technologies as may be developed and matured in SEI missions will be available for SPS-related missions and vice versa.

9.0 LIKELIHOOD OF SUCCESS

Microwave technology in the ISM band of 2.4 to 2.5 GHz is sufficiently mature that no schedule or performance risk has been identified. What is required is the normal equipment development process for a well-focused application where, compared to existing large phased array radars, less sophistication is

FIGURE 3. WORLD MAP SHOWING LOCATIONS OF HIGH POWERED (BLACK) TRANSMITTERS FOR LEO TO GEO TRANSPORATION SYSTEM. LOW POWERED (WHITE) TRANSMITTERS ARE FOR PROPOSED "ORBITING INDUSTRIAL PARKS"

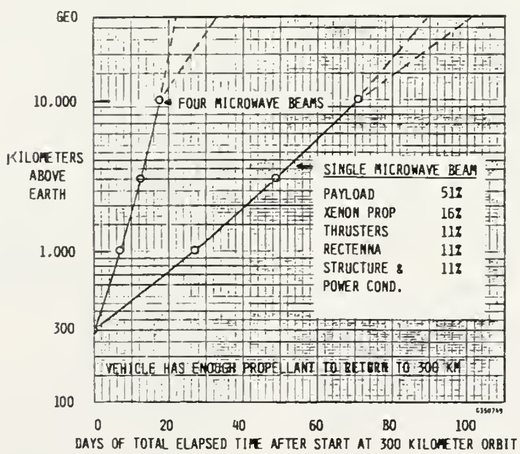

FIGURE 4. ORBITAL ALTITUDE OF IOTV AS FUNCTION OF TOTAL ELAPSED TIME FOR A ONE BEAM AND FOUR BEAM SYSTEM

necessary and primary emphasis will be not so much on performance as on deployability, ruggedness, producibility, reliability, maintainability, and general operability as well as on societal considerations, low nonrecurring and recurring cost goals including those of the total life cycle. The opportunity for use of large numbers of identical components (Microwave Oven type Magnetrons at the transmitter end (Ref. 7) as well as Schottky-Barrier GaAs diodes at the receiving and rectification end) is key to successfully completing a "low-risk" program implementing this "IDEA". Both of these key components have matured by their extensive useage in the prolific ISM band (including specific developments in the Solar Power Satellite - related application).

Areas within the "Power Beaming" equipment that could benefit from further investigation (Ref 2) include: Transmitting Antenna; Rectenna; Power Conditioning; The unknown aspects of the impact of material outgassing on electrical leakage across the Rectenna; and Beam pointing problems related to the nonhomogeneous atmosphere.

Areas of interfacing with Electronic Thrusters that could benefit from further investigation (Ref 2) include plasma backstreaming from the exhaust of the electric thrusters, and associated need for simplification of power conditioning. These and other investigations require further careful design integration and development that are considered to be technically straightforward and manageable when work packages are properly defined, assignments are properly made, and responsibilities assumed.

10.0 KEY DEMONSTRATIONS

Feasibility of the elements and end-to-end system chain for microwave power beaming has been established. The Rectenna portion, where major skepticism existed, has been demonstrated and certified (Ref 3 and 9), under Contract No. NAS 7-100 in May 1975.

End-to-end total system applications, such as the Microwave Powered Airplane are under development in Canada (as a market venture) with sub-scale flights having been accomplished and with nearer-full-scale total system demonstrations being formulated for near-future implementation (Ref 2.).

A progressive development plan has been formulated for the Solar Power Satellite application, where power is beamed from Space to Earth (Ref. 8). However, a similar plan for Earth to Space Power Beaming is yet-to-be-defined. Such a demonstration program must be thought through and conducted with essential rigor.

11.0 ESTIMATED COSTS

Estimated costs for the Microwave Power Beaming system are broken down into the cost of the ground segment and space segment of the system. These costs do not include the ground power source of prime power, the space vehicle, and electric thrusters.

The estimated cost for a single baseline Full Power Prototype ground-based segment is from 0.8 to 1.5 billion dollars. The baseline transmitter has an antenna area of 2 million square meters and emits a maximum microwave power of 500 megawatts. A single transmitter system is adequate for many applications, especially for transporting the large scale payloads characteristic of the SPS to a staging node in HEO and to GEO as well as for transporting equipment back to LEO or other interorbital transportation. A mature system, capable of handling a much higher rate of mass transfer to GEO and consisting of four transmitters, would cost in the range of 3 to 4 billion dollars. These estimates are based upon more detailed previous assessments of transmitter cost, prepared for microwave powered airplane systems and for supplying power to orbiting industrial parks in LEO. The estimated transmitter costs are contingent upon first constructing a low power 200 x 200 meter array estimated to cost from 80 to 100 million dollars. This array would incorporate all the technology to be used in the larger transmitter and would be capable of beaming 20 megawatts of continuous rf power to LEO for collection and use in industrial parks, as well as for constructing and powering the large electric powered IOTV and the appropriate portions of the SPS while they are being integrated and transported.

The estimated cost of the 50,000 square meter Rectenna array used on the baseline 20 megawatt dc electric powered IOTV is 100 to 150 million dollars. The cost of Rectennas for a mature system that would consist of a fleet of four vehicles each rated at 100 megawatts dc is estimated to be under one billion dollars. Estimates are based upon well established costs of the printed circuitry and the rectifying diodes which comprise the Rectenna.

Operating costs would consist largely of the primary energy obtained from electric utilities or other power sources on the ground. The energy consumption of a one-beam baseline system would be of the order of 4000 Kw-hrs for each kilogram of payload delivered to GEO. At a charge of 10 cents per Kw-hr, this would amount to $400/Kg. In a mature system, with its improved aperture-to-aperture efficiency, these costs could be reduced by a factor of from five to ten.

12.0 MILESTONES

Sequence and time estimates, for phases of the System Acquisition Cycle are as shown in Figure 5.

13.0 OTHER IMPORTANT FACTORS

Other currently known factors that should be considered in evaluating this "IDEA" derive from recognition of the following:

Applications of equipment in the microwave (2.4 to 2.5 GHz) band [commonly referred to as the Industrial, Scientific, and Medical (ISM) band] have been exceedingly numerous and the biological effects as well as electromagnetic interference, compatibility and associated protective techniques are well understood. This is not to say that there is complete freedom at microwave frequencies. Rather, the constraints are best understood at microwave (ISM band) frequencies and must be complied with.

Power beaming at higher or otherwise out-of-this band different frequencies (millimeter wave, Laser, etc.) will need to be accompanied by extensive investigations to ensure that constraints are sufficiently well understood and waste heat dissipation can be accomplished satisfactorily.

There are about a dozen different Nations resident on the equator which offer opportunities for cooperative international enterprise. Legal, national and international policy as well as security factors (with both positive and negative implication) must be taken into account.

14.0 LIST OF ACRONYMS

AIAA	-	American Institute of Aeronautics and Astronautics
GBT's	-	Ground Based Transmitters
GEO	-	Geosynchronous or Geostationary Earth Orbit
HEO	-	High Earth Orbit (Altitude to be derived in "Trade Investigations" for near-optimization of requisite architectural and design integrated attributes).
IOTV's	-	Interorbital Transport Vehicles
ISM Band	-	Industrial Scientific and Medical Band (2.4 to 2.5 GHz)

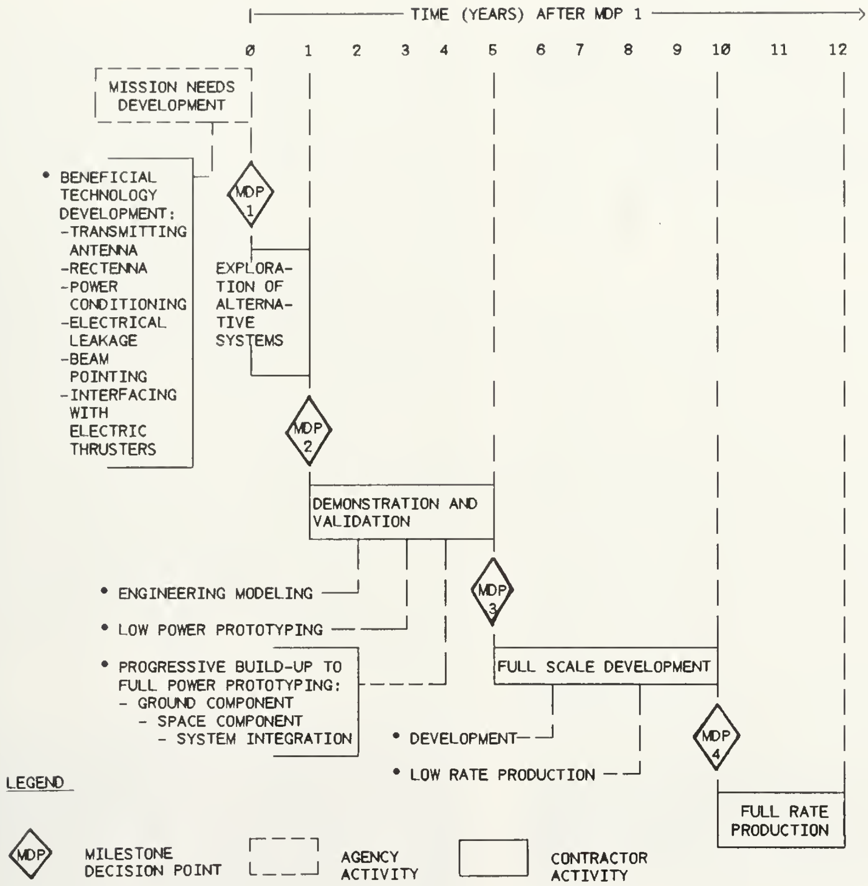

FIGURE 5. SEQUENCE AND TIME ESTIMATES FOR SYSTEM ACQUISITION

LEO	-	Low Earth Orbit (Region of "FREEDOM" class space station altitudes)
MDP	-	Milestone Decision Points
NASA	-	National Aeronautics and Space Administration
RECTENNA	-	Receiving and Rectifying Antenna
rf	-	Radio Frequency
SEI	-	Space Exploration Initiative
SPS	-	Solar Power Satellite
	-	Space Power Stellite

15.0 LIST OF REFERENCES

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B7.1 The Magnicon as a highly efficient, high power, high frequency source for space power beaming

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ABSTRACT

Efficiency is one of the crucial figures of merit for a cw microwave source for space power beaming. At frequencies higher than X-band, the magnicon becomes a very attractive candidate source. A conceptual point design is given here for a cw magnicon at X-band having an efficiency of about 85 %, a power of 200 kW, and a gain of 18 dB.

RESUME

Le rendement est une des caractéristiques primordiales d'une source permanente de micro-ondes en transmission de puissance dans l'espace. Pour les fréquences supérieures à la bande X, le magnicon devient un candidat très intéressant comme source d'émission. Un projet spécifique est présenté ici pour un magnicon en ondes entretenues dans la bande X avec un rendement de 85 % environ, une puissance de 200 kW et un gain de 18 dB.

For space power beaming, a crucial figure of merit for any system is the overall efficiency. For instance, Brown has developed a system based on 2 kW magnetrons at S band, which is 50% efficient, DC to DC, so long as the receiving antenna, the rectenna, is fully illuminated by the source.[1] For future space power beaming applications, which would involve greater distances, higher power and higher frequency sources would be required. At higher frequency, the highest power cw sources are gyrotrons. Varian, for instance, has developed a cw gyrotron at 140 GHz and 100 kW.[2] However the efficiency is only about 30%, and furthermore, it is a free–running oscillator rather than an amplifier or phase–locked oscillator. Thus multiple sources cannot be coherently combined.

A new microwave source which could have the potential for operation at high frequency, high average power and high efficiency is the magnicon. This source has been developed in the Soviet Union as a source to power accelerators.[3] So far, the Soviet work has been at a frequency of about 1 GHz, although designs have also been proposed at 7 GHz.[4] The beam wave interaction in a magnicon, however is very similar to that of a gyrotron. Thus it should be possible to extrapolate a magnicon to much higher frequency. Recent analysis at NRL,[5] which also focused on the application of powering large linear colliders, has come up with a conceptual design of a magnicons at X and K_u–band. Here we give a conceptual point design of an X–band magnicon more relevant for space power beaming. The design parameters are a power of about 200 kW with an efficiency of about 80–90%.

The magnicon is an example of a swept beam device,[6] that is a low power rf signal deflects the beam so that it enters an output cavity properly phased so that all electrons have the same interaction with the wave there. This then eliminates one of the difficulties of a klystron or gyroklystron, in which some of the electrons are inevitably phased to gain rather than lose energy. Since all electrons have the same motion, the energy recovery from the spent beam should be simplified compared with that of gyrotrons and klystrons.

A qualitative description of the magnicon is as follows. An electron beam passes through the center of a TM_{11}–mode cavity in which a mode with azimuthal rotation is set up externally. As the beam transits the cavity, it is given an angular deflection which also rotates azimuthally at the drive frequency. The beam then propagates in free space, and moves away from the axis at its deflection angle. At some point down stream, there is a magnetic half–cusp. The linear motion of the beam is then converted to cyclotron motion, and since the beam has zero canonical angular momentum, its cyclotron orbits thread the axis. Then the magnetic field is

compressed and the beam perpendicular energy increases until it enters the output cavity. Note that the entrance angle of the electron rotates in time at the drive frequency. The resonant frequency of the output cavity is tuned to be equal to the drive frequency or one of its harmonics. In this way, the beam gives all of its transverse (cyclotron) energy to the fields of the output cavity. A much more complete description of the theory of the magnicon is given in Ref. 5.

Since there is a large region of free, unguided propagation of the beam from the entrance of the first cavity up to the entrance of the cusp, the magnicon is inherently a relatively high voltage, low current device. There are two propagation conditions which must be satisfied. In the region from the entrance of the first cavity to the cusp, the beam radius must be small compared to the transverse wavelength. We assume a radius of 3 mm. Secondly, at the entrance to the cusp, the beam must have a sufficiently small radius to make it through the half cusp without significant energy spread due to the geometric extent of the beam at the entrance. We assume that the beam must maintain a focus of 1 mm as it transits the half cusp. With soft iron pole pieces, cusps which change by 1 kG over a centimeter or two have been demonstrated.[7] If the current is too high, the beam will spread due to a combination of space–charge and emittance, and will not satisfy the above constraints.

We consider then a magnicon at a relatively high voltage and low current. In the magnetic fusion program, the neutral beam sources are driven by DC power supplies at 150 kV, and we assume this as an available DC voltage for a power supply. As we will see, a current of 2 Amps then gives rise to reasonable beam propagation, and this is the current we will assume. Furthermore, our point design will convert 80% of the beam energy to transverse energy, and the remaining 20% will be assumed to be collected with a depressed collector. The energy dissipated in the wall will be about 30 kW (about 350 W/cm^2), so the efficiency will be between 80 and 90%, depending on how close one can come in practice to the theoretical efficiency of 87%.

The requirements on the focusing system are most relaxed if one operates at low amplification. We assume this for our initial point design. In this case one can use a single deflecting cavity and a single solenoidal focusing coil at the entrance to the deflecting cavity. We assume an input power of 3 kW, so the amplification is less than 20 dB. However we assume 3 kW driver sources are available, since these do not have to be very efficient.

We now proceed with the point design. Additional details of the the theory can be found in Ref. 5. The distance a beam of radius r_b can travel before its own space charge forces blow it apart is given by

$$L_s = r_b/K^{1/2}\ , \tag{1}$$

where

$$K = 1.2\text{x}10^{-4} I(A)/(\gamma^2-1)^{3/2} \tag{2}$$

and γ is the relativistic factor. The 2 Amp, 150 kV beam can then travel 5 cm at a radius of 1 mm (through the cusp), and a distance of 15 cm at a radius of 3 mm (up to the entrance of the cusp). The distance the beam can travel against its own emittance forces is given by

$$L_\varepsilon = r_b{}^2/\varepsilon \tag{3}$$

where ε is the emittance in rad–cm, and lengths are in centimeters. Since beams of this sort[8] can be produced with emittances of about 10^{-3}, the propagation distance is about 10 cm for a 1 mm radius beam, and about a meter for a 3 mm beam.

The first cavity is designed to have length L_1 so that $\omega L_1/v_z=\pi$, where ω is the angular frequency and v_z is the electron velocity. For our case of 10 GHz, $L_1 = 1$ cm. The cavity is assumed to be excited in a TM_{11} mode. If the electric field amplitude in the first cavity is given by E_1 the deflection angle ζ is given by

$$\zeta = 0.42 e E_1/\gamma m c \omega\ , \tag{4}$$

where all units are Gaussian. The power into the cavity is related to the field by

$$E_1{}^2 = P(\text{Watts})Q/60 \tag{5}$$

where Q is the cavity quality factor. If the Q=5000 (In Ref. 5, it was shown that for this Q and beam current, the vacuum Q should be nearly equal to the beam–loaded Q), and the power input is 3 kW, then the angular deflection is about 0.05 radians.

For an X–band magnicon at cyclotron frequency resonance, driven by a 150 kV beam, the magnetic field in the cavity is given by 4.6 kG. If the half cusp is at a field of 1 kG and the field is further compressed to its final value where 80% of the beam energy is transverse, it is shown in Ref. 5 that the distance from the output of the first cavity to the entrance to the cusp is about 13 cm.

We now consider the design of the TM_{11} output cavity. We assume that the maximum field that the wall can sustain in cw operation is 50 kV/cm, which means a field amplitude E_2 of $1.4\text{x}10^3$ in cgs units. If the frequency is at cyclotron resonance, the length of the second cavity, L_2 is given by

$$0.11 e E_2 v_t L_2/mc^3 = 0.8(\gamma-1) \tag{6}$$

Thus the second cavity works out to have a length of 5 cm. In this distance the beam loses its transverse energy, or about 240 kW. The Ohmic Q of the TM_{11} cavity is given by

$$Q_{OH}{}^{-1} = \omega(1+a/L_2)\delta/3.8c\ , \tag{7}$$

where a is the cavity radius for the TM_{11} mode (1.9 cm) and δ is the skin depth, assumed to be 6.6×10^{-5} cm for copper. Thus of the 240 kW of power the beam loses, about 25–30 kW are deposited in the cavity walls as Ohmic heating. Since the spent beam should be nearly monoenergetic, an energy recovery scheme for it should be quite straightforward. Thus the final point design for an X–band magnicon should generate about 210 kW of cw power with an efficiency of about 85%. Such a source could be very attractive for space power beaming. Although the frequency of the design we have chose is 10 GHz, the actual maximum frequency could be much higher by operating at higher magnetic fields and at higher harmonics. As the field and harmonic number increases, tolerances become more precise. The actual upper limit to the frequency is an area for future research. The conceptual design of the 210 kW X–band magnicon at 18 dB amplification is shown below.

Acknowledgment

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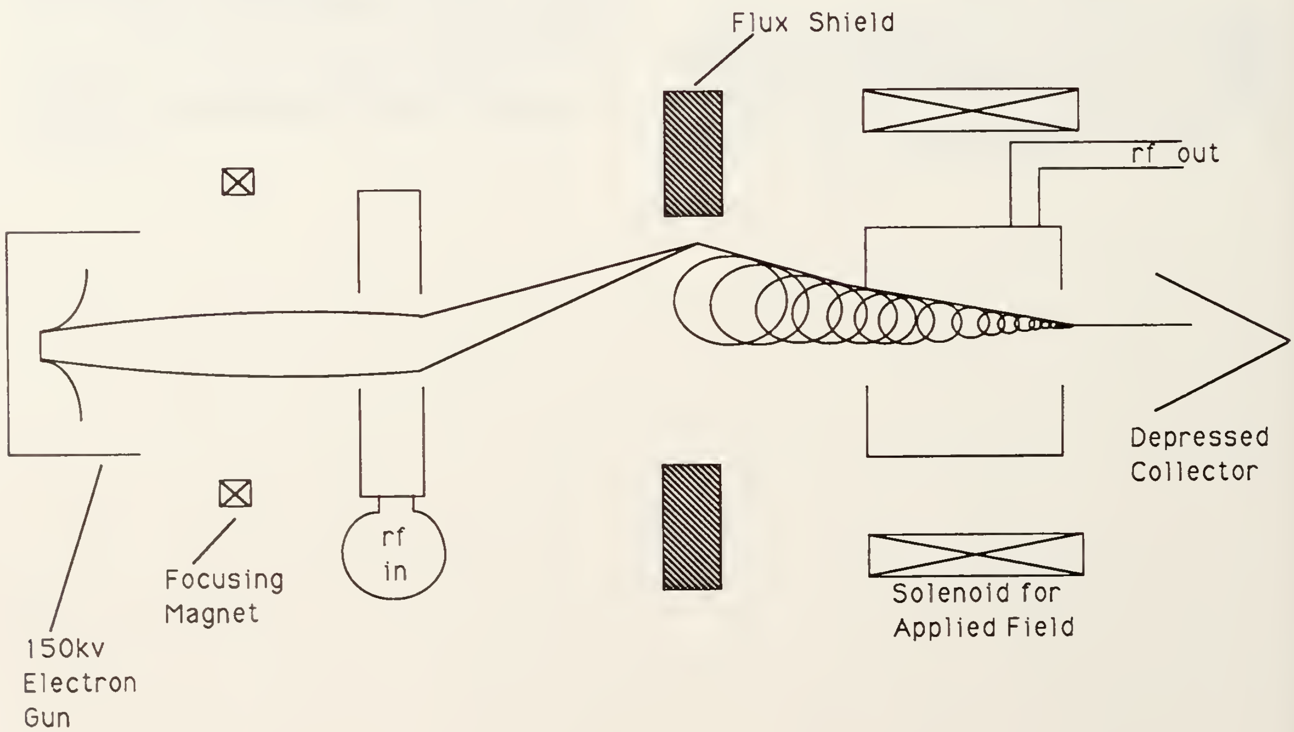
Schematic of a Magnicon for Space Beaming



B7.2 Cyclotron-wave converter for SPS energy transmission system

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ABSTRACT

It was shown the possibility of cyclotron-wave converter (CWC) realization with power level up to 100 kW, output voltage up to 100 kV, efficiency to 85-90 percent and high reliability. The perspectives of CWC application in the SPS ground station are discussed in comparison with rectenna elements based on Schottky-barrier diodes.

RESUME

On montre la possibilité de réaliser un convertisseur à ondes cyclotroniques (C.O.C.) à un niveau de puissance montant jusqu'à 100 kW et une tension jusqu'à 100 kV. Le rendement est de 85 à 90 % et la fiabilité très élevée. On discute les perspectives de l'utilisation des C.O.C. dans les stations électriques solaires terrestres en les comparant aux éléments des systèmes Rectenna à base de diodes Schottky.

1. Introduction

Design of special microwave rectification devices for the SPS energy transmission system was based on the application of the Schottky-barrier diodes with very low inner losses and, therefore, with high conversion efficiency [1-4]. Antenna consisting of a set of half-wavelength dipoles with aligned Schottky diodes was called rectenna and was thoroughly investigated for quite a long time [5-8]. The rectenna efficiency exceeded 80-85 percent both in laboratory condition and in the field test for power levels from several hundred W to 30 kW accordingly [6-8].

However, some principal difficulties easily overcome in laboratory experiments can arise at the stage of rectenna application on the SPS scale. It is important to underline the following problems:

1. The high level of SPS power (5 GW) and the low specific power of a single Schottky-barrier diode (less than 2-6 W) will require a very large number (more than 10^9) of elements in the SPS rectenna. This will entail a great expense of the rare materials (Pt, GaAs) and will increase the losses in connection circuits and lines. The production, maintains and prophylactic measures of the rectenna will be, therefore, rather difficult.

2. The low output voltage of the Schottky-barrier diodes (10-20 V) will require their connection in series. This will reduce the system reliability and, furthermore, will need a large number of high-voltage and high-frequency insulators (up to 200 elements on sq.m.) capable to function at any meteorological conditions over several decades under comparatively high voltages (3 kV in General Electric Co. version [9]).

3. The low stability of Schottky-barrier diodes may result in their avalanche breakdown caused by overloads that may appear during the rectenna operation and may be caused by switches, short-circuits in connection lines, microwave radiation of the atmospheric discharges etc.

The analysis of these problems leads us to the conclusion that their solution is inevitable connected with an increase of output power, output voltage and stability of a single converter. These requirements could be more satisfied by electron-beam microwave devices and the cyclotron wave converter (CWC) could be distinguished among them.

The preliminary CWC investigations [10,11] were based on the theoretical analysis with an excessively simplified model containing a filamentary electron beam and zero space charge. This did not produce an opportunity to define correctly the parameters of laboratory devices and obtain the high conversion efficiency.

The CWC analysis [12-16] have demonstrated the possibility of high efficiency conversion of microwave energy into dc energy (up to 85-90 percent) by means of the high-power and high-voltage cyclotron-wave converters.

2. Physical progresses in CWC

The principle of CWC operation may be illustrated by Fig.1. Externally applied microwave power at

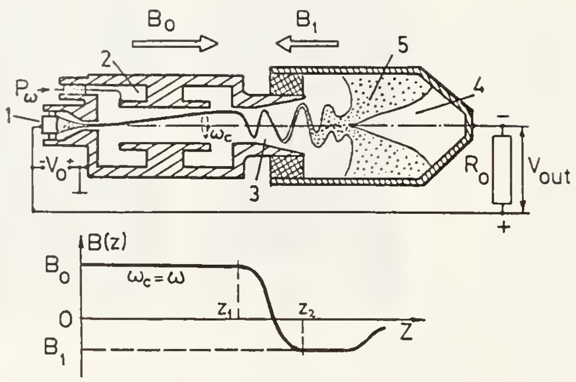

Fig.1
Structural scheme of the cyclotron-wave converter with the reversed magnetic field.
1 - electron gun, 2 - resonator with the transverse microwave electric field, 3 - conversion region with the reversed magnetic field, 4 - depressed collector, 5 - electron beam, P_ω- input power, V_0- anode voltage, V_{out}- output voltage, R_o- collector load resistance, B_0 and B_1- the resonant and reversed magnetic field accordingly.

frequency ω induces electromagnetic oscillations with the transverse electric field in the coupler gap of the resonant cavity 2 (Cuccia coupler[17]). Electron beam 5 formed by the electron gun 1 obtains cyclotron rotation at cyclotron frequency ω_c under the action of external magnetic field and the microwave oscillation in the resonant cavity. The applied microwave power, thus, may be transformed completely into electrons rotational power, if cyclotron resonance conditions (ω=ω_c) are fulfilled. The resonant cavity is followed by conversion region 3, where the external magnetic field changes both the direction and the magnitude. In the reversed magnetic field electrons rotational energy transforms into the energy of accelerated electron beam longitudinal motion. Simultaneously, the electron beam configuration is changed - the rectilinear beam takes the spatial helix shape. The electron accelerated in the conversion region enter depressed collector 4, where their kinetic power is converted into dc power. The load circuit current equals the electron beam current in the absence of electron interception.

The CWC resulting efficiency η_{CWC} may be defined by the input microwave power P_ω, CWC output voltage V_{out} and load resistance R_o as:

$$\eta_{CWC} = V^2_{out} / (R_o P_\omega) \tag{1}$$

as long as the source of the electron gun anode voltage V_o does not spend energy by normal operation conditions, i.e. without beam interception.

The spatial separation of the main CWC parts (resonant cavity, conversion region, collector) gives an opportunity to put into practice their successive and independent analysis. We took into consideration such factors as:

1) the finite diameter of electron beam cross-section[13-15];
2) the electron beam space charge[14-15];
3) the secondary electron emission from the collector surface[15], that may considerably influence on the CWC conversion efficiency.

The computer investigation of the microwave power conversion into electron beam rotation in the resonator was performed and relativities increase of the electron inertial mass was taken into account. Besides, we were obliged to pay attention to the influence of the microwave field magnetic component in case of extremely high-power CWC.

The voltage and configuration of the collector electrodes and the magnetic field variation along the axis of the device were optimized in order to get the maximum CWC efficiency.

3. CWC Power.

The investigation of the CWC specific power indicates the possibility of the CWC realization in the wide range of input power - from several hundred W to 50 kW and more[13]. It is characteristic of the CWC that their input microwave power level may essentially exceed the electron beam power itself, i.e.:

$$W = P_\omega / I_o V_o >> 1. \tag{2}$$

The increase of the anode voltage V_o up to the relativities values would give an opportunity to raise the CWC power up to several hundred kW. However, the most preferable value for the upper level of input power could be limited by 50-100 kW due to a danger of microwave breakdown in the resonant cavity and to a considerable change of the external magnetic field along the resonator length.

4. Efficiency of microwave power conversion

It is convenient to express the CWC efficiency as:

$$\eta_{CWC} = \eta_{res} \cdot \eta \cdot \eta_{coll} \tag{3}$$

where η_{res}, η, η_{coll} are the efficiencies of the transformation processes in the resonant cavity, conversion region and collector correspondingly.

The resonant cavity efficiency η_{res} may be found, if the values of its unloaded quality factor Q_o and its loaded quality factor Q are known, i.e.:

$$\eta_{res} = 1 - Q/Q_o \tag{4}$$

The typical values of the CWC resonator quality factors Q and Q_o are 20-30 and 2000-3000 accordingly. Thus,we obtain the resonator efficiency η_{res} equal 0.985- 0.983.

The possibility of the CWC efficiency optimization was revealed by the digital investigation of the electron beam rotational power conversion into its longitudinal motion power in the region with the non-symmetrically reversed magnetic field[14]. It was shown that the conversion efficiency η could reach 0.85-0.9 level for any limited conversion region length, if the magnetic field profile on the axis was optimized.

The computer investigation of space charge influence on the conversion efficiency shows that the efficiency decrease will not occur, if the electron beam current does not exceed 0.5-0.75 of its Brilluen value - I_{Br} (Fig.2). A certain gain of the conversion efficiency at these current values may be explained by some acceleration of the slowest electrons under the space charge field longitudinal component occurring due to the electron beam distortion.

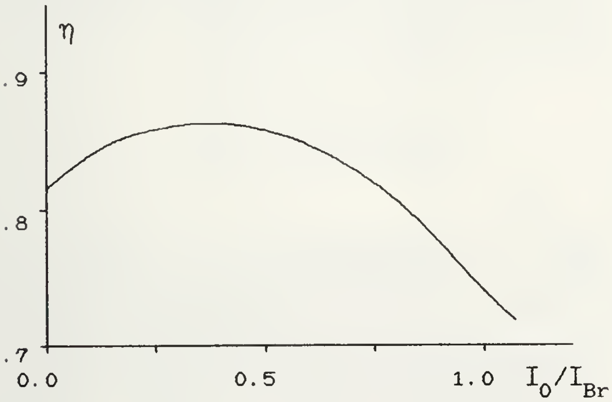

Fig.2

Typical behavior of the conversion efficiency η versus the electron beam current. I_{Br}- Brilluen electron beam current value at the gun output.

Both the electron beam acceleration and its transverse dimension increase will reduce the space charge density and the possibility of the electron reflection from the collector region. The reverse current of the secondary electron emitted from the collector surface is of the main danger. The computer analysis of the electron beam power recuperation proved that this problem might be solved by the formation of a potential barrier for the secondary electrons in the depressed collector region. A certain increase of the collector main electrode voltage (i.e. a certain decrease of absolute value V_{out}) will lead to a slight reduce of the CWC resulting efficiency (about 1-2 percent), but will eliminate the reverse current of the secondary electrons completely. The collector efficiency η_{coll} may reach 0.92-0.96 level.

5. CWC output voltage

The CWC output voltage range may be extended up to hundred kV and more by using relativities electron beam. However, the realization of these output voltage values will meet serious problems because of the appearance of the electron velocity dispersion caused by the microwave magnetic component in the resonant cavity. Furthermore, it may be accompanied by a decrease of power factor W. Thus, it may be more preferable to place an upper limit at the output voltage level about 100 kV.

The typical parameters of several CWC versions defined on the basis of the previous papers[12-16] are summarized in Table 1. The last two columns correspond to frequency of 10 GHz that may be used for the purpose of the power exchange between the space vehicles or their power feeding by microwaves radiated from the SPS or the Earth surface.

6. CWC exploitation reliability

It is necessary to underline the low CWC sensitivity to various kinds of overload that may happen during their exploitation.

The CWC protection from the input microwave power overload may be reached at the expense of the electron beam current limitation. The anode voltage V_o of the electron gun may be applied through a high-ohmic resistance because of the negligibly small current in that electrical circuit. The CWC overload by input microwave power will cause the electron beam interception by the capacitor plates of the resonator and, thereby, will abruptly diminish the anode voltage and the electron beam current.

The same effect will provide CWC protection from any collector overload caused by abrupt increase of the load resistance in the collector circuit (circuit breakage due to switching etc.). The appearance of the electron reflected from collector region will lead to their interception by the resonator plates or the drift tube and, thereby, will limit the electron beam current.

The collector overload connected with any short-

Table 1

Input frequency, GHz	2.45	2.45	2.45	10.0	10.0
Input microwave power, kW	10	50	100	10	25
Conversion efficiency, %	87.4	86.0	86.4	87.4	88.0
Output voltage, kV	23	107.5	108	23	23.7
Electron beam current, A	0.38	0.4	0.8	0.38	0.93
Electron gun anode voltage, kV	10	10	10	10	10
Initial electron beam radius, mm	1.1	1.7	1.7	1.7	1.7
Resonant magnetic field, G:					
a) at the resonator input	892	892	892	3.642	3.642
b) at the resonator output	937	1.104	1.104	3.825	3.825
Conversion region length, mm	73	121	121	18	59
Reversed magnetic field, G	187	110	110	765	383
Diameter of the electron beam helix at the end of the conversion region, mm	37	77	77	9.6	15.1
Power dissipated on the collector, kW	1.3	7	13	1.3	3

current circuit in the collector electrical chain may be of a great danger because of considerable increase of the dissipated power. However, this may be foreseen by the collector construction to avoid an overheat of the collector.

The CWC contains thermocathode with a limited life time and requires an additional power source that may be considered as the main CWC disadvantage. However, to overcome this difficulties in the Earth condition is much easier than in the Space, where klystrons and magnetrons with the same thermocathodes were discussed as a basic device for the microwave amplification in the transmitting antenna[3,18,25].

7. CWC application in SPS ground station

The receiving antenna of the SPS ground station may consist of parallel rows of the microwave reflectors (parabolic troughs) forming an elliptical aperture[16]. The incident SPS microwave beam is concentrated on the slotted waveguide array in two-dimensional horn. The length of the slotted waveguide sections loaded on the CWC (Fig.3) may be different and depends on the input power in the given region of the receiving antenna. The surface efficiency of such antenna may reach 95 percent and more.

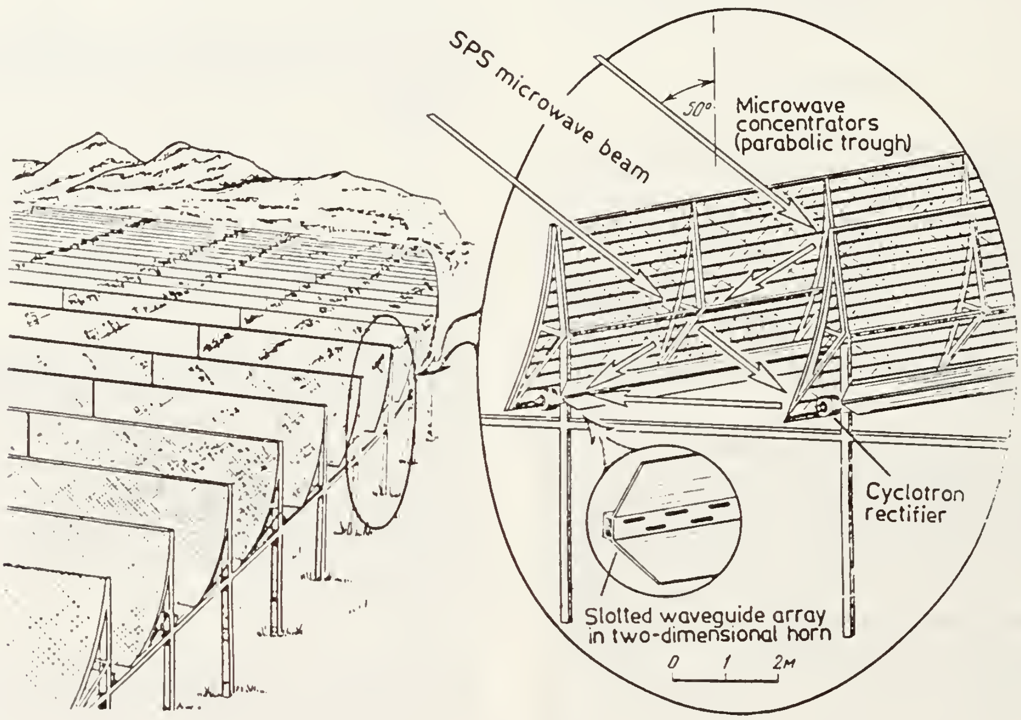

Fig.3
Drawing of a version of a ground receiver and conversion complex for SPS using cyclotron-wave converters (site latitude is 50^{o}).

Fig.4 presents a sketch of the CWC intended for operation in the SPS ground station.

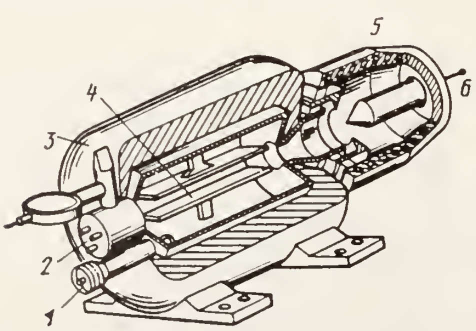

Fig.4
Scheme of CWC version for the SPS ground station. 1 - input of microwave power, 2 - electron gun, 3 - magnetic system, 4 - resonator with the transverse microwave electric field, 5 - collector, 6 - output voltage.

The resonant cavity interaction gap is formed by a strip line with rectangular cross-section. The reverse current of secondary electrons emitted from the collector surface may be reduced by means of the potential barrier formed by the collector electrodes[15].

Both the rational concentrator dimensions and the optimal power of single converter are essentially related to the flux density of the SPS microwave power. Although the preliminary values of the microwave flux density have been defined - 230 W/m^2 in the rectenna center and 10 W/m^2 on the rectenna edge[3,9] - this question is still at the stage of clarification and quantitative definition of the ionosphere and medical limitations[7,19-24]. The investigations showed that microwave flux density could be at least doubled and would not induce any noticeable ionosphere perturbation[24].

The application of powerful, high-efficient and high-voltage cyclotron-wave converters in the SPS energy transmission system will enable us to

Table 2

SPS output power, GW	5.0	5.0
Rectifier type	Schottky diode	CWC
Single rectifier efficiency, %:		
a) achieved	85	80
b) expected	90-95	90-95
Single rectifier power, W	2-6	10^4-10^5
Number of rectifiers in the SPS ground station	more than 10^9	10^5-10^6
Single rectifier output voltage, V	10-20	10^4-10^5
Necessity of the rectifier connection in series	yes	no
Insulator density, m^{-2}	200	10^{-2}
Stability to the overload	low	high
Additional power source	no	yes
Second harmonic problem	yes	no
Radiation sensitivity	high	low

reduce the total number of conversion elements and obtain high rectenna efficiency, to avoid converter connection in series and to secure the receiving system stability against microwave or dc overload. The comparative characteristics of the SPS ground stations based on the Schottky-barrier diodes and the CWC are summarized in Table 2.

8. Summary

It should be noted in conclusion that rectenna with the Schottky-barrier diodes played a fundamental role at the stage of demonstrating a principal probability of the high-efficiency power transmission by means of the microwave beam.

However, the application of the semiconductor rectenna in the real SPS ground station may involve certain difficulties. Therefore, the powerful, high-efficient and high-voltage cyclotron-wave converters may prove to be more preferable for this purpose[26].

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B7.3 Microwave sources for power transmission in space

M. FIRMAIN et al. - Thomson Tubes, Vélizy, France

SUMMARY

The electrical energy, produced by a space based power sation, has to be transmitted to users either on earth or in space. Transmission using microwave beams, as for all other technologies (laser, tethers) has advantages and inconveniences, on which base the final technology will be chosen, but not for many years. One main advantage of using microwaves is that high-power RF sources exist for ground applications, as well as beam forming systems. This paper describes the present status of microwave tube technology, limited to the best candidates for SPSs. It is shown that reasonable efforts towards space qualification of tubes could lead to operational sources by the year 2000.

RESUME

L'énergie électrique produite par une sation spatiale doit être transmise aux utilisateurs, qu'ils soient sur terre ou dans l'espace. La transmission par des faisceaux microondes, comme toutes les autres technologies (lasers, câbles) à des avantages et des inconvénients, qui seront pris en compte dans le choix final. Un des avantages principaux à l'usage des microondes est que les sources HF de grande puissance existent pour les applications terrestres, ainsi que les systèmes de génération des faisceaux. Ce papier décrit l'état actuel de la technologie des tubes hyperfréquences, pour ceux qui sont les meilleurs candidats pour des stations génératrices en orbite. On montre qu'un programme raisonnable de qualification spatiale des tubes peut conduire à des sources opérationnelles en l'an 2000.

1. Microwave transmission of energy

A renewal of interest has been observed for the concept of space power stations, aimed at producing electrical energy and transmitting it to users, either terrestrial electrical distribution networks or remote satellites.

In the early concepts, in the seventies, energy transmission from the station in geostationary orbit to earth, was performed using microwave beams at 2.45 GHz. Since then, other technologies, such as laser beams have become candidates for energy transmission.

All technologies raise numerous technical, regulatory or environmental questions, which will take many years to solve. This time will certainly be useful for these technologies to evolve toward maturity for such an application.

It is not the purpose of this paper to compare the various technologies for energy transmission. It is rather to show that microwave transmission may be available sooner than others and may well serve at least for experimental stations, aimed at developing the other technologies needed for SPS.

One application where the regulatory, environmental and technical aspects seem less crucial than for transmission of energy to earth, is the transmission of tens to hundreds of kilowatts of power from a power station in space (powersat) to users in space at kilometers of distance. In this case, a very efficient transmission through microwaves could be achieved within a few years (by 2000, for example), using antennas of reasonable sizes and high power sources with high efficiency, high reliability and reasonable cost.

In this paper, we describe the best candidates for such sources, these being, microwaves tubes, already existing for ground applications. The effort to space qualify such tubes is also discussed. An example is given of what will be available by the end of the century for a demonstration station.

2. Single or combined sources

The cost and performances of a microwave transmission system are closely related to the power level to be transmitted and to the frequency of the carrier. It is desirable to, firstly, use the highest frequency possible, to reduce the antenna and rectenna sizes, while increasing the distance of transmission for a given efficiency, and, secondly, to minimize the launch and construction costs of the station.

The situation is totally different concerning high power microwave tubes. As shown later, state-of-the-art tubes show that power capability decreases rapidly with increasing frequency, roughly as I/F squared. Their cost increases accordingly.

To transmit a given amount of power at a given frequency, the most cost effective of the two following solutions will have to be selected :

- the first using a single source if the very high power tube is available for the application. The transmit antenna would then be of standard nature, with feed horn and attitude control using thrusters.
- the second, using combined sources with several lower power tubes. In this case, another choice exists, depending upon the way the individual tubes are combined :
  - . output signals from the tubes may be added in-situ through hybrids, with proper phasing, to feed the standard antenna. This is an usual technique in telecommunications and direct broadcast satellites ;
  - . or each tube amplifier feeds one horn of a phased array antenna, which achieves a spatial summation of the signals at the desired location, e.g, the user's rectenna. This technique is well known and used in the radar domain.

While the single source transmitter may use either oscillators or amplifier tubes, the combined source transmitter must imperatively use tube amplifiers, as the signals have to show phase coherency.

However, the combined sources transmitter has technical and economical advantages that make it the best candidate for microwave power transmission.

Table 1 lists some interesting advantages of paralleling tubes, compared to a single tube source.

TUBES
- Far below state of the art
- Higher reliability
- Easier to space qualify
- Lower thermal loading
- Lower voltages
- Scale effect on production
- Lower overall cost including non recurring one
SYSTEM
- Easier thermal control
- Still operationnal (while degraded) in case of one tube failure
- Simpler redundancy scheme

TABLE 1 - ADVANTAGES OF PARALLELED TUBES

Further advantages of the phased array antenna make this transmitter an attractive candidate to beam microwave energy toward users.

First, beam pointing is electronically controlled, through computer driven phasing of each source amplifier, reaction time may be microseconds, reliability and reproducibility are quite high, compared to mechanical beam steering, and attitude control of the station may be simpler.

Second, beam forming may minimize side lobes amplitudes, leading to lower power losses and reduced environmental pollution by microwaves.

Third, non negligible advantages of the phased array antenna are related to the implementation of the sources over the whole surface of the antenna. They are :

- heat dissipation with much reduced thermal flux
- lower losses, as the amplifiers outputs are directly connected to the emitting horns ;
- modular construction, making the assembly of the station in space easier ;
- enhanced reliability, through the graceful degradation concept.

Obviously, the advantages listed in table 1 for tubes still apply. Hereafter, we will present sources using exclusively microwave tubes. Transmitting large amounts of power (hundreds of kilowatts), if solid-state amplifiers were to be used, would require about 100.000 SSPA modules unless solid-state technology rapidly progresses in the coming years. Such a large number of modules would be unrealistic to manage.

3. Microwave tubes, state-of-the-art

The above discussion on microwave power transmitters has shown that microwave sources are not restricted, by any means, to the most powerful tubes. We can consider using the whole range of tubes covering the CW power, frequency domain.

Figure 1 shows the state of the art of the dominant vacuum and solid-state power source technologies.

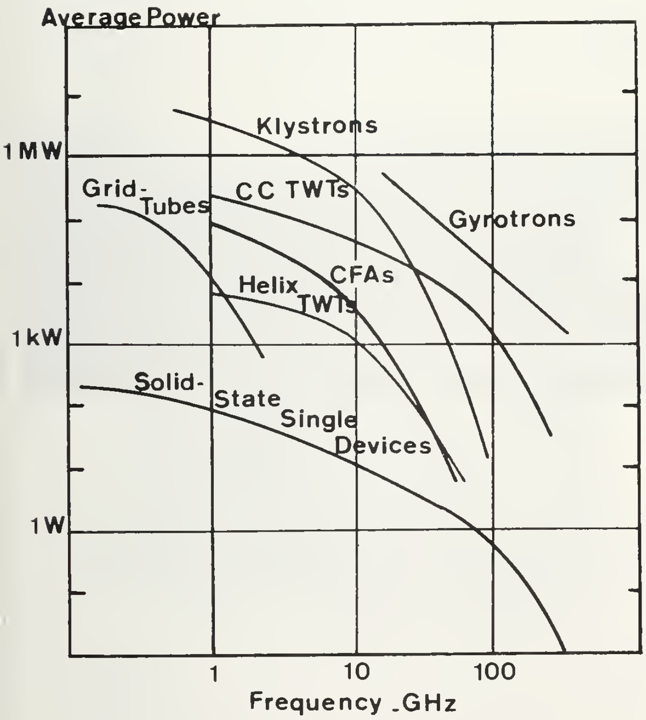


FIGURE 1 : POWER FREQUENCY ACHIEVEMENT

The figure clearly indicates that vacuum devices are best suited to high power transmission at a given frequency, as they are 1000 to 100.000 times more powerful than solid-state devices. It also shows the frequency limitations of various type of tubes : table 2 lists the frequency beyond which the achievable power is below ten kilowatts average.

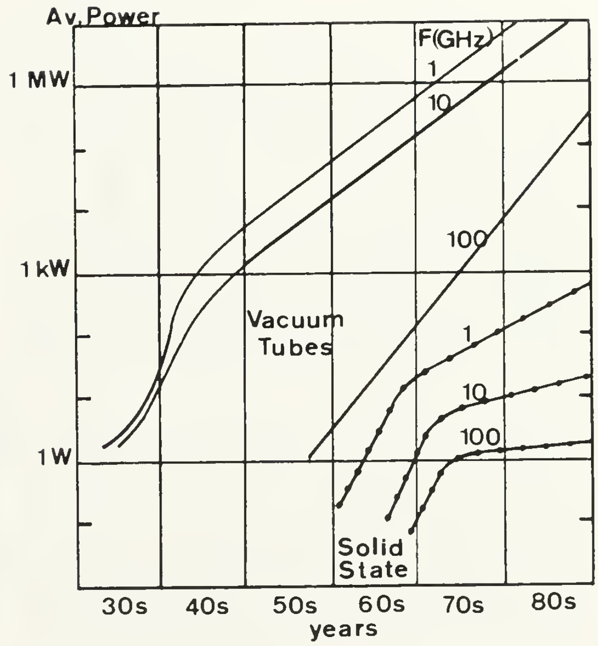
TUBES	FREQUENCY ($Po = 10^4$ watt)
Gridded tubes	1 GHz
Crossed-field tubes	10 GHz
Klystrons	30 GHz
Coupled-cavity TWTs	30 GHz
Fast-wave tubes	300 GHz

TABLE 2 - POWER CAPABILITY OF VACUUM TUBES

The historical evolution of vacuum tubes in the power frequency domain is also impressive, as shown by figure 2.

Power capability at 100 CHz has reached a power growth rate of 1.6 dB/year, mainly due to rapid progress of the gyrotron and other fast-wave devices.

At lower frequencies, the power capability has a more modest growth of about 1.0 dB/year because the more classical tubes (magnetrons, klystrons, TWTs) have mature technologies.



FICURE 2 : HISTORICAL EVOLUTION OF VACUUM TUBES AND SOLID STATE

We will show later that gyrotrons have been developed for this relatively low frequency range, which will be capable of producing tens of megawatts in the near future. On the other hand, solid-state devices show slower growth in power performances, amounting at 0.3 - 0.8 dB/year.

Microwave tubes are, in essence, high power devices, because the thermal loading (in watt/sq.cm), the main limiting factor of all power devices is not a radidly varying function of power at a given frequency.

There are several categories of microwave tubes which cover the frequency spectrum up to 300 GHz or more. Their applications on ground are well known :

- radar and countermeasures ;
- telecommunications ;
- industrial, scientific and medical sources.

Not all microwave tubes are candidates as sources for energy transmission from a space based power station. This is so because such an application has specific requirements, making some tubes more suitable than others. Table 3 lists some of these requirements, which may affect the choice of RF source.

High efficiency (60-70 %)
Long life (10 years)
Low weight, compacteness
Reduced high voltages
Survivability of launch
Broadband not necessary

TABLE 3 - SPECIFIC REQUIREMENTS

In the next section, each tube type is briefly described and the main characteristics are discussed in conjunction with the above specific requirements.

4. Microwave tubes

All microwave tubes are based on the same principle of transferring part of either kinetic or potential energy of free electrons in a vacuum to an RF field carried by a microwave structure. The primary energy of the electrons is supplied by high accelerating voltages generated by a power supply.

4.1 Gridded tubes

In the low frequency rang of the microwave spectrum (i.e. hundreds of megahertz), gridded tubes, triodes and tetrodes, have been considerably improved over their eighty years of existence. They are now capable of several hundred kilowatts average, and feature high efficiency, compactness and good lifetimes.

One frequency limitation of gridded tubes is the transit time of the electrons between the grids and anode.

4.2 Linear beam tubes

This transit time, on the contrary, is used in linear beam tubes, such as klystrons and traveling-wave tubes. The microwave operation of the linear beam tubes is based on three successive actions :

- a periodic modification of the electron velocities by a field , either that of a cavity (klystrons) or that of a periodic structure (TWTs) ;
- grouping of the electrons into bunches, under the influence of this velocity modulation ;
- excitation of a cavity or a periodic structure by the passage through its field of the electron bunches. The microwave energy that the beam gives back to the RF structure is obtained from the electrons kinetic energy.

4.2.1 Klystrons

Figure 3 shows a cross section of a simplified four-cavity klystron.

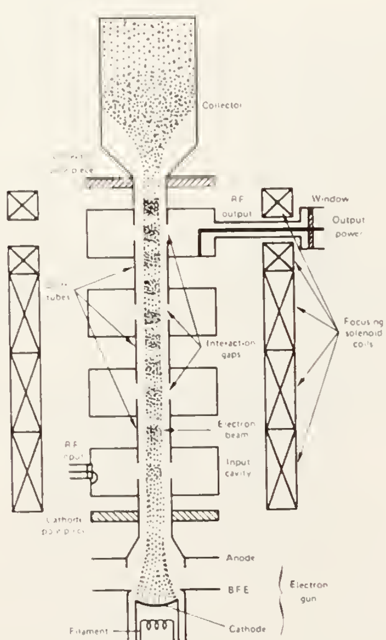


FIGURE 3 : CROSS-SECTION OF A 4 CAVITY KLYSTRON

Klystrons operating at about 300 MHz, with an output power of 1.3 megawatt CW, are now in production for fusion applications or particle accelerators. They have high efficiencies (70 %) but are heavy devices, measuring several meters in length (figure 4). At about 4 GHz, high power klystrons can produce more than 700 kW of CW power.

At such low microwave frequencies, gridded tubes and klystrons woulb be suitable for large power plants, e.g. moon based, feeding antenna arrays of several hundred square kilometers.

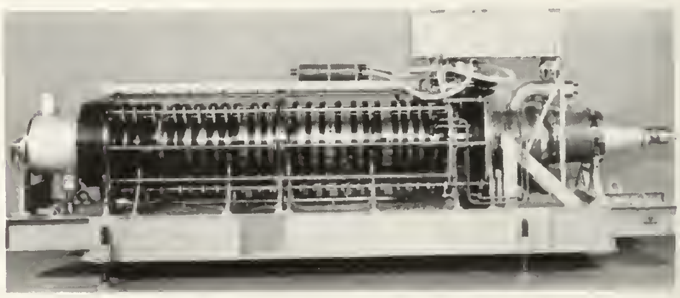


FIGURE 4 : ONE MEGAWATT CW, 352 MHz KLYSTRON

At higher frequencies (10-30 GHz) the klystrons can produce CW powers of 100 kW down to 10 kW and would find applications in smaller size satellite power stations.

4.2.2 Traveling wave tubes

Another linear beam tube, competing favourably with the klystron above 30 GHz, is the coupled-cavity, solenoid focused, traveling-wave tube, capable of producing up to one kilowatt of average power at 100 GHz. Traveling wave tubes are generally used in applications requiring wide bandwidths. Their efficiency is continuoûsly improving through modern techniques of velocity tapering and multi-depressed collectors (MDC). In MDCs, part of the remaining kinetic energy of the electrons is recovered, which boosts the efficiency. As an example, efficiencies as high as 60 % are now achieved with 100 watt CW, Ku band space TWTs. Although the broadband operation of TWTs is not necessary for microwave power transmission, these devices remain candidates to feed arrays in the 10-100 GHz range.

4.3 Crossed-field tubes

In linear beam tubes, the general direction of electron beam motion is aligned with the DC electric and magnetic field. In the crossed-field tubes, the general motion of the beam is perpendicular to both fields. The electrons leaving their emitter (cathode) follow trajectories which close in on an RF structure (anode) with which they interact. The RF structure is either a series of resonators (magnetrons) or a slow wave structure (crossed field amplifiers or oscillators).

4.3.1 Magnetrons

The magnetron is the oldest, most well known tube, because of its use in microwave ovens.

It is a low cost, compact, rugged, lightweight tube, featuring high efficiency, as high as 80 %. Its high power capability, however is limited to a narrow frequency range. Magnetrons delivering several hundreds kilowatts at about 900 MHz are in production for industrial heating. At 10 GHz, magnetron power capability is currently limited to a few hundred watts CW. Another limitation to its use in space is a rather short life of a few thousands hours. Figure 5 shows a 6 kW-2,45 GHz industrial microwave heating magnetron.

FIGURE 5 : A MAGNETRON FOR INDUSTRIAL HEATING

4.3.2 Crossed-field amplifiers

The name crossed-field amplifier designates quite a large variety of tubes, distinguished from each other by the following characteristics :

- an injected beam or a distributed emission ;
- a linear or circular construction ;
- a cold or a hot cathode ;
- a forward or a backward moving slow-wave.

All CFAs have in common a lower gain than TWTs or klystrons, a high efficiency (50 to 70 %), compactness, small input to ouptut phase shift, making it easy to operate these tubes in parallel, and lower operating voltages than linear beam tubes.

The CW power capability of CFA's is now limited to about 500 kW in L-band, and decreases rapidly with frequency (kilowatts at X-band).

4.4 Fast-wave tubes

4.4.1 General

In the conventional microwave tubes described above, the RF waves are slowed to remain in synchronism with the electron velocity. A completely new concept, revolutionized the microwave tube industry, twenty years ago : this is the fast-wave device, where the RF structure is usually a smooth waveguide or a large resonator in which no attempt is made to reduce the velocity of the wave, but the electron beam is injected into the electromagnetic field in such a way that interaction can take place. In other words, the relatively slow electrons always "see" an accelerating or decelarating field, so that bunching occurs.

Many fast-wave devices are still in the early research and development phase, but in the future might be attractive as very high power sources, covering the total microwave spectrum and above. However, their availability for an operational satellite power system is not foreseen before several decades (except gyrotrons).

Table 4 lists some fast-wave devices, the development of which should be carefully followed by the space community.

DEVICE	FREQUENCY RANGE GHz
Vircator	0,8-6
Relativistic magnetron	1-5
Gate effect klystron	1-17
Relativistic klystron	5-30
BWO, Orotron	10-30
Gyrotron	10-200
CARN, Cerenkov maser	30-200
Free electron laser, maser	10 to infrared

TABLE 4 - FREQUENCY RANGE OF FAST-WAVE DEVICES

Among these devices, the gyrotron merits special attention for two reasons ; first, the gyrotron is capable of producing hundreds of kilowatts to megawatts over a large part of the microwave spectrum. Second, the gyrotron has already left the laboratory phase to enter industrialisation and production for some applications.

4.4.2 Gyrotrons

In gyrotrons, a hollow beam immersed in a strong magnetic field, is divided into many beamlets with high rotational energy (figure 6).

In the interaction region, the beamlets interact with a TEm,n waveguide mode, such that an electron always sees an accelerating or decelerating field.

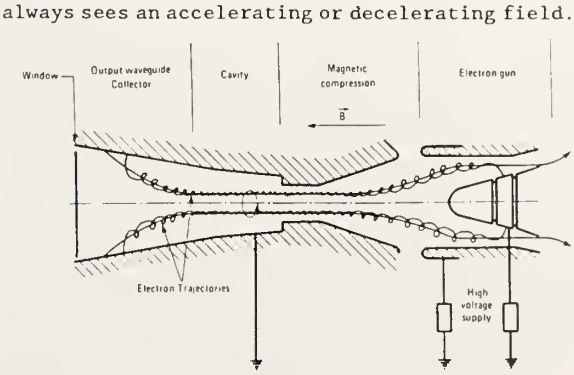


FIGURE 6 : STRUCTURE OF A GYROTRON

The salient characteristics of gyrotron devices and their implications are :

- circuit areas in gyro devices are about 100 times the area in conventional tubes, which means that they have 100 times more power capability ;
- the frequency of operation is proportional to the axial magnetic field, which means that fairly low frequency (10 GHz) gyrotrons require standard electromagnets, while millimetric gyrotrons require superconducting magnets.

Figure 7 presents the power capability of gyrotrons compared to conventional tubes. This plot obviously changes year after year, as the progress in performances are quite rapid.

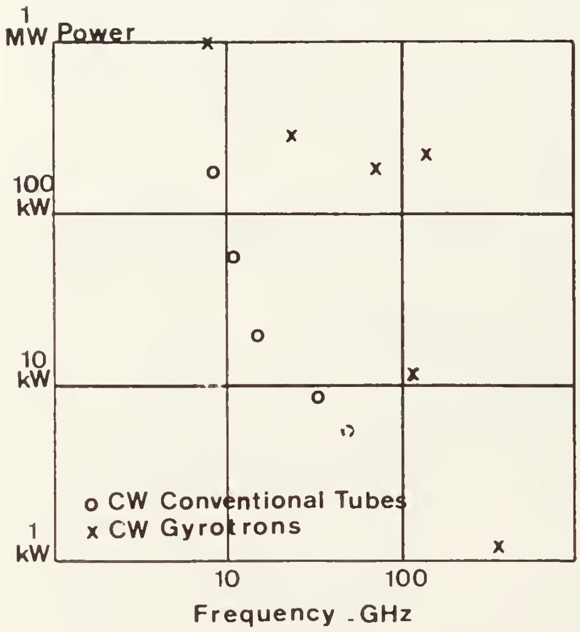


FIGURE 7 : GYROTRONS CW POWER OUTPUT VERSUS FREQUENCY COMPARED TO CONVENTIONAL TUBES

Examples of quasi-CW performances of gyrotrons, now in production or in advanced development, are given in table 5.

Frequency	GHz	8	100
Output power	kW	1000	210
Pulse duration	S	1	0,1
Efficiency	%	45	30
Circular mode		TE51	TE34
Magnetic induction	T	0,3	4
Voltage	kV	90	80
Weight	kg	700	70
Length	m	3	2,5

TABLE 5 - GYROTRONS CHARACTERISTICS (EXAMPLES)

Figure 8 shows the 8 GHz gyrotron (scale is about 1/25). These devices are mainly oscillators, but amplifiers, such as gyro-klystrons and gyro-TWTs are under development and could be used in combined power sources.

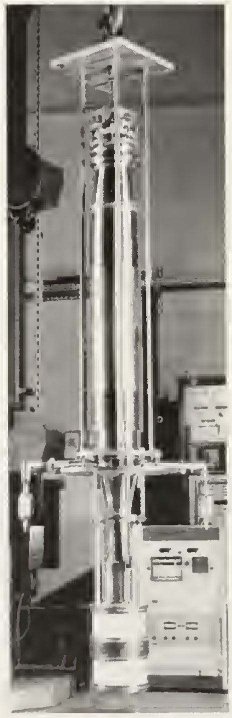


FIGURE 8 : ONE MEGAWATT, 8 GHz GYROTRON

They are heavy and large sized and use magnets weighing several hundred kilograms. Their mechanical design would not be compatible with the launch environment. Moreover, they need large power supplies, complex cooling systems, and various accessories such as mode transducers. These features mean that significant development has to be carried out before they can be used in space.

4.5 Summary

The above description of the best candidates for microwave power transmission in space should not be considered as exhaustive. It shows that hundreds of kilowatts to megawatts can be produced in the full microwave frequency range, by various types of tubes. Some are in mass production, generally at the lower end of the spectrum, others are in advanced development and the remaining, but most promising, are still in the laboratory phase. Of course, tubes of more modest power at given frequencies, exist, at least on earth, capable of feeding large arrays to transmit power through spatial summation. However, space qualification requires additional works so the sources may be used in space-based power stations.

5. Tube space qualification, areas of development

Use in space of high power tubes would require the solution of various engineering problems, as well as improvement in the life and reliability of the tubes.

5.1 Engineering

The following developments would be necessary to improve microwave-tubes performances, to enable their use in space.

Efficiency enhancement

Increasing tube efficiencies for ground applications has not been a key design objective. We can live with efficiencies of 30-50 %, except in some industrial applications, and megawatts range.

However, techniques exist, to increase efficiency such as :

- multi-depressed collectors ;
- velocity tapering ;
- harmonic injection ;
- loss reduction ;
- use of low dielectric constant materials.

These techniques have proven effective for low-power space tubes. For example, 100 watt, Ku band TWTs for communications satellites now have more than 60 % efficiency.

For high-power tubes, an objective of 70-80 % at low microwave frequencies, and 50 % at about 100 GHz seems achievable within a ten-year time frame.

Reduction in mass

Again mass and size are not primary objectives in designing ground tubes. Power tubes are heavy, but a large margin exists for weight reduction. 50 % reduction should be realistic. Not only the tube, but also the surrounding equipment (magnets, power supplies, accessories) should receive attention in this field.

Thermal control

Much of the power supplied to the tubes is lost at heat, requiring complex cooling systems. With higher efficiencies, heat losses are reduced. However, thermal control systems should still be improved.

Radiating cooling and superconductivity are promising techniques in this field.

Mechanical ruggedness

While some high-power tubes are designed for air borne applications, most others would not survive the mechanical conditions experienced during launch. Improvements in this field must be carried in conjunction with reduction in mass.

Power conditioning

All power tubes operate with high voltages in the range of tens to hundreds of kilovolts, produced by large, heavy power supplies. If the use of high voltages is unavoidable, power conditioners of reduced size and weight must be developed.

This is achieved through the use of switching frequencies of up to 100 kilohertz. These power conditioners require special designs and careful optimization of their interface characteristics.

5.2 Life and reliability

High-power tubes have lives of a few thousands hours, and some, in the kilowatt power range, may reach a few tens of thousands of hours.

There is one - and only one - main element limiting the life of a tube : this is the electron emitter or cathode, because it operates at high temperatures (1000 - 1100° C). The higher the power-frequency product, the higher is the burden on the cathode.

For operational use in space, lives of ten to fifteen years (130 000 hours) should probably be required.

There is an apparently difficult to fill gap between the lives presently achieved and those required.

However, rapid progress is being achieved in the field of cathodes. As an example, lives of low-power space tubes are expected, and have been demonstrated through modeling techniques, to be more than twenty-five years. This is achieved using new cathode types, already space qualified.

Furthermore, new cathodes are being developed which are capable of delivering high currents for more than ten years. They will be available in time to replace the conventional cathodes, now in use in high-power tubes.

Reliability is also an important factor to consider. To avoid unnecessary redundancy, an MTTF of one million hours over ten years of mission life (60 % confidence level) should be a minimum for a single tube high-power source.

Using multi-tube sources, or phased arrays, would probably require less, thanks to the graceful degradation concept.

The present reliability figure for high-power tubes is certainly not acceptable : MTTF may be estimated as a few tens of thousands of hours.

There is much to be done to improve tube reliability, through process control, failure mode identification and correction, appropriate burn in and strict selection.

Tube technology is mature for ground applications. Further development and qualification efforts, would probably take ten years, leading to space qualified sources by the year 2000.

6. Possible application

Power transmission using microwave beams may or may not be the final choice for transmission technology from a satellite power station to users. However, the power sources exist, and may well serve for experiments aimed at developing the other technologies, such as energy production. A possible application of microwave transmission might be a small satellite station, providing kilowatts of power, to be transmitted to other satellite users at kilometers of distance. This "powersat" concept is being seriously considered, at least in Europe.

At this level of power, microwave transmission could be operational in a time frame of 7-10 years, using an active antenna, with a hundred low power sources. Such sources, e.g. 100 W - Ku band TWTAs, are now in production for telecommunications and direct broadcast satellites.

While having modest power and transmission distance capabilities, such an application would constitute a first step towards larger SPS's, using a microwave transmission system of reasonable cost.

7. Conclusion

High-power microwave tubes are a mature technology and microwave power transmission from a spacecraft is on the verge of being a feasible solution.

There is a large choice of high-power tubes in this power-frequency domain. This paper has concentrated on those which are in production or advanced development for ground applications.

Although, their use in space would require intensive additional efforts of development and qualification, they could be available for operational use much earlier than other transmission technologies.

Furthermore, low power sources are readily available for a kilowatts-powersat by the year 2000 or sooner.

B7.4 Antenna synthesis for the SPS microwave transmission system

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ABSTRACT

Promising application of the SPS microwave power transmission system with radially polarized field at the antennas is discussed. It is shown that in this case more power can be transmitted at a reduced electricity cost.

RESUME

Une application prometteuse du système SPS de transmission d'énergie microonde, présentant un champ polarisé radialement, est discuté. On montre que, dans ce cas, il est possible de transmettre plus de puissance à coût d'électricité réduit.

1. Introduction

Synthesis of the optimal field distribution at the transmitting antenna of the SPS microwave power transmission system (MPTS) is very important, because the MPTS characteristics, such as collection efficiency, sidelobe level, transmission power, electricity cost, etc. depend on field distribution.

Synthesis of the electric field distributions over the transmitting antenna which provide the maximum collection efficiency (the ratio of the power received to the power transmitted) has been studied thoroughly[1,2]. It has been shown that polarization at the transmitting antenna should be uniform. The phase distribution provides a focused beam at the center of the receiving antenna. A Gaussian taper is a good approximation to an optimum aperture distribution. It is the field distribution that was chosen in the DOE/NASA SPS reference system[3].

In subsequent studies[4-7] it was pointed out that it was not only the collection efficiency but also the sidelobe level near the receiving antenna, electricity cost, etc. that are very important in power transmission and optimization methods for this characteristics were proposed.

Arndt et al. proposed aperture illumination synthesis method for the SPS antenna[4]. The developed amplitude distributions provide some advantages over the 10 dB Gaussian taper was chosen in the reference system, such as reducing electricity cost and sidelobe level (43.6 mills per kWh and 0.01 mW/cm^2 instead of 46.8 mills per kWh and 0.08 mW/cm^2 for the reference system, 1 mill = 0.001 dollar).

In our papers discrete 10-step amplitude distributions for the SPS antenna were generated[6,7] which provide the sidelobe level that is lower than both the USSR medical standard (10 $\mu W/cm^2$) and the standard for the electromagnetic compatibility (0.27 $\mu W/cm^2$).

But in those papers it was only amplitude distributions that were generated. The polarization at the transmitting antenna was assumed to be uniform. The phase distribution was not optimized and was assumed to provide a focused beam at the center of the receiving antenna, i.e. the phase distribution and field polarization correspond to those obtained in the problem of collection efficiency maximization.

The MPTS with radially polarized field on the antennas[8] is also promising as well one can improve the MPTS characteristics by optimizing the phase distribution[9].

The present study deals with synthesis of amplitude-phase distributions over the transmitting antenna with uniform and radial polarization providing the minimal electricity cost based upon cost model[4] while the minimizing sidelobe level to meet 0.01 mW/cm^2 USSR medical standard. For this purpose the antenna synthesis method has been developed.

2. The SPS microwave transmission system with radially polarized field at the antennas

Assume the electric field at the circular antenna aperture to have only radial component depending on the radial distance from antenna center only

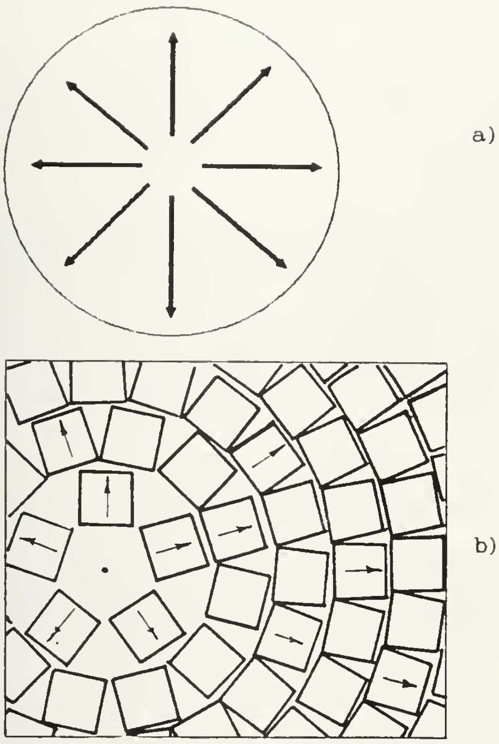

Fig.1
a - Circular antenna with radially polarized field. b - Fragment of antenna array with radially polarized field. Arrows - direction of electric field.

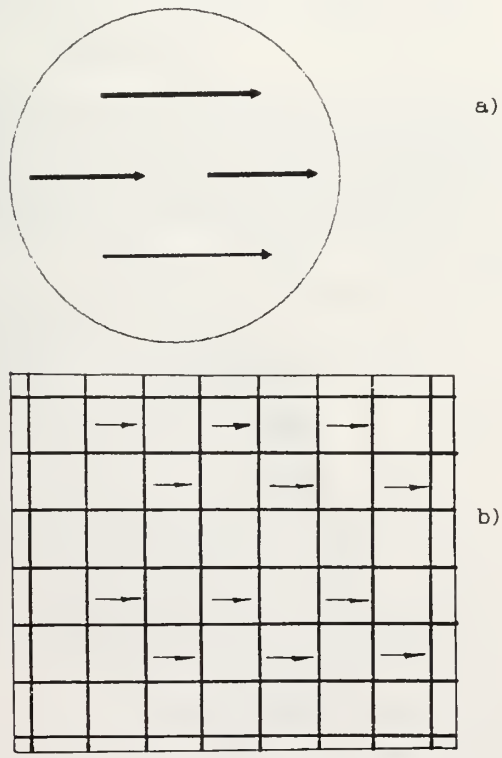

Fig.2
a - Circular antenna with uniformly polarized field. b - Fragment of antenna array with uniformly polarized field. Arrows - direction of electric field.

(Fig.1a). Such a field structure can be realized in practice by means of a phased antenna array composed of the same radiation modules as those of an antenna array with uniform polarization (Fig.2), the modules being arranged as ring bands (Fig.1b). The electric field at the radiation module is uniformly polarized and the field amplitude at the modules of each band is constant. For a field with the above structure to be received one can use the antenna composed of receiving-rectifying modules arranged in a similar way.

The preliminary analysis reveals a number of advantages of such a system over the MPTS with uniformly polarized field at the antennas. Using the radiation modules of 10-100 wavelengths (i.e. 1-10 m with the wavelength of 10 cm) the suggested arrangement allows the level of the the antenna array diffraction (far) lobes to be reduced considerably, which is a serious problem for the SPS microwave power transmission system with uniform polarization[10]. Also it is to be noted that the axial symmetry (Fig.1) eliminates the requirement for the receiving and the transmitting antennas to be mutually oriented in the azimuth angle, which is important for antennas with uniform polarization (Fig.2).

What values of the collection efficiency will correspond to antennas with radially polarized field? It can be shown that the maximum efficiency value, as in the case of uniform polarization, will provide a quadratic phase distribution focusing a beam at the center of the receiving antenna. In our paper the amplitude distributions providing the maximum value of the collection efficiency between antennas with radial polarization were obtained[8].

Fig.3 represents the maximum value of the collection efficiency η and the transmitting and receiving antenna power coefficients W_a and W_r (the ratio of the average power density to the maximum power density) versus the wave parameter τ for antennas with uniform and radial polarization[8].

For the same values of parameter τ (i.e. for the same radii of antennas) the system with radial polarization corresponds to lower values of the collection efficiency than those for the system with uniform polarization. In order to obtain the given efficiency values for antennas with radial polarization it is necessary to use the values of τ ~1.5 times greater than those for antennas with uniform polarization.

Fig.4 shows the efficiency-optimal normalized amplitude distributions at the transmitting antenna and the corresponding normalized power density distributions in the the receiving antenna plane. One can see that because of the power density maximum being shifted away from the beam center, the antennas with radial polarization have the antenna power coefficients 1.5-2.5 times greater than antennas with uniform polarization (Fig.3-6). Therefore, if the values of maximum power density at the antennas are limited, in the case of radial polarization more power can be transmitted and received.

Note also that the sharp minimum at the beam center (Fig.6) can be used to improve beam pointing of the transmitting antenna to the receiving one.

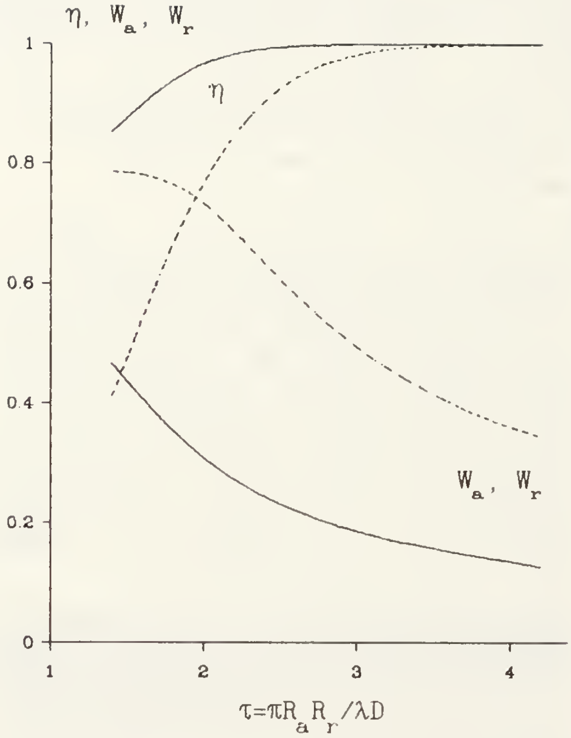

Fig.3
Maximum value of the collection efficiency η, transmitting and receiving antenna power coefficients W_a and W_r versus wave parameter τ. In this case $W_a \approx W_r$. R_a, R_r - antenna and rectenna radii, λ - wavelength, D - distance between antennas. Solid line - uniform polarization, dotted line - radial polarization.

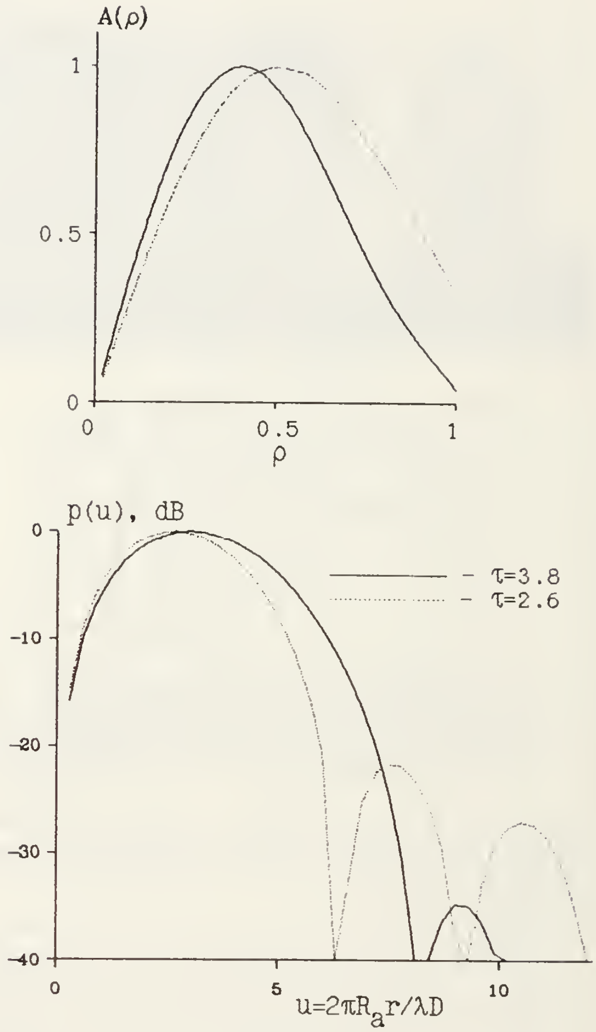

Fig.4
Efficiency-optimal normalized amplitude distributions at the transmitting antenna A(ρ) and the corresponding normalized power density distributions at the receiving antenna plane p(u) in the case of radial polarization. ρ - normalized by R_a radial coordinate at the transmitting antenna plane, r - radial coordinate at the receiving antenna plane.

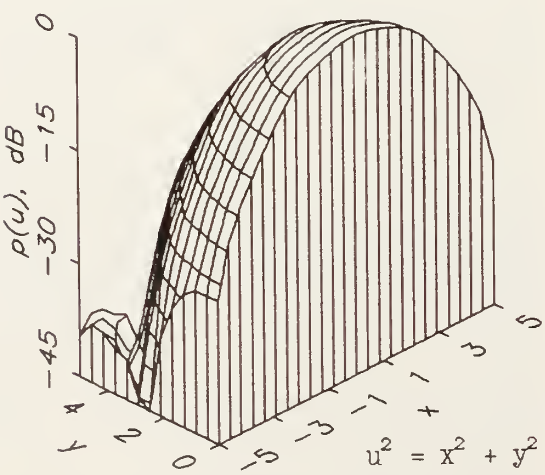

Fig.5
Typical form of normalized power density distribution at the receiving antenna plane in the case of uniform polarization.

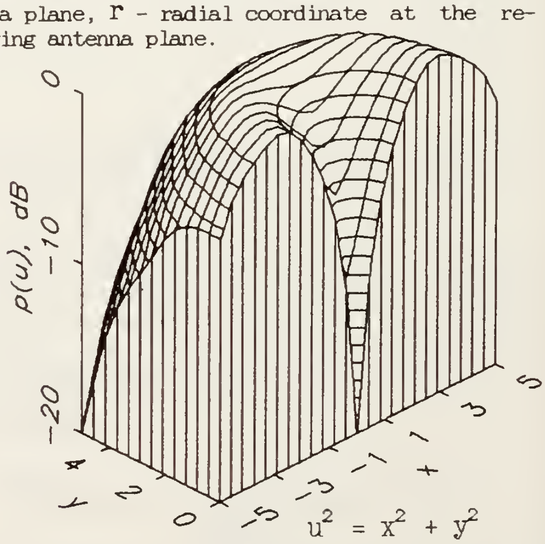

Fig.6
Typical form of normalized power density distribution at the receiving antenna plane in the case of radial polarization.

3. Amplitude-phase distribution synthesis method

This section describes the synthesis method for amplitude and phase field distributions at the transmitting antenna. The main idea of the method is as follows.

The field distribution at the transmitting antenna (a complex function) is expanded in a series of real partial distributions with complex coefficients. Various types of polarization can be described by an appropriate choice of partial distributions. Hence the synthesis problem becomes that of finding unknown complex coefficients providing the optimal characteristics. To find the unknown coefficients the method of penalty functions[1] can be used.

Below the main formulae used for calculating and optimizing the SPS characteristics are given.

The SPS transmitting antenna can be considered as a circular aperture with a continuous field distribution because the dimensions of radiation modules are much less than the antenna radius.

The power density distribution in the receiving aperture plane has the form:

$$p(u) = p_{a\ max} \cdot \left[2\pi R_a^2 / \lambda D \right]^2 \cdot |F(u)|^2 \qquad (1)$$

where $u=2\pi R_a r/\lambda D$,

λ - wavelength,
D - the distance between the antennas,
R_a - transmitting antenna radius,
r - radial coordinate in the receiving aperture plane,
$p_{a\ max}$ - the maximum value of power density at the transmitting antenna.

Function $F(u)$, accurate up to the constant multiplier, coincides with the radiation pattern of the transmitting antenna and is expressed by:

$$F(u) = \int_0^1 A(\rho)e^{-i\varphi(\rho)}J_0(u\rho)\rho d\rho \qquad (2)$$

in the case of uniform polarization and

$$F(u) = \int_0^1 A(\rho)e^{-i\varphi(\rho)}J_1(u\rho)\rho d\rho \qquad (3)$$

in the case of radial polarization, where

$\varphi(\rho) = \pi\rho^2 R_a^2/\lambda D - \varphi'(\rho)$,
ρ - radial coordinate normalized to R_a in the transmitting aperture plane,
$A(\rho)$ and $\varphi'(\rho)$ - amplitude and phase distributions at the transmitting antenna,
$J_0(u\rho)$ and $J_1(u\rho)$ - Bessel functions of first kind of zeros and first order.

Thus, if the quadratic phase distribution focusing beam at the center of the receiving antenna is realized, the function $F(u)$ is real. In the general case the function $F(u)$ is complex.

The field distribution function over the transmitting antenna is expanded in a series of real partial amplitude distributions with complex coefficients (x_n+iy_n):

$$A(\rho)e^{i\varphi(\rho)} = \sum_{n=1}^{N}(x_n+iy_n)\cdot a_n(\rho), \qquad (4)$$

In this case one can obtain the following expressions:

$$F(u) = \sum_{n=1}^{N} (x_n+iy_n)\cdot f_n(u), \qquad (5)$$

$$f_n(u) = \int_0^1 a_n(\rho)J_0(u\rho)\rho d\rho \text{ (uniform)}, \qquad (6)$$

$$f_n(u) = \int_0^1 a_n(\rho)J_1(u\rho)\rho d\rho \text{ (radial)}, \qquad (7)$$

$$p(u) = p_{a\ max} \cdot \left[2\pi R_a^2 / \lambda D \right]^2 \times \sum_{n,m=1}^{N} (x_n x_m + y_n y_m)\cdot f_n(u) f_m(u) \qquad (8)$$

where $a_n(\rho)$ and $f_n(u)$ are partial amplitude distributions and partial radiation patterns (real functions).

The expression for the collection efficiency has the form:

$$\eta = P_r/P_a, \qquad (9)$$

$$P_r = 2\pi R_a^2\, p_{a\ max} \int_0^{2\tau} |F(u)|^2 u du = 2\pi R_a^2\, p_{a\ max} \sum_{n,m=1}^{N} (x_n x_m + y_n y_m)\cdot C_{nm} \qquad (10)$$

$$P_a = 2\pi R_a^2\, p_{a\ max} \int_0^{\infty} |F(u)|^2 u du = 2\pi R_a^2\, p_{a\ max} \sum_{n,m=1}^{N} (x_n x_m + y_n y_m)\cdot B_{nm} \qquad (11)$$

$$C_{nm} = \int_0^{2\tau} f_n(u) f_m(u) u du, \qquad (12)$$

$$B_{nm} = \int_0^{\infty} f_n(u) f_m(u) u du, \qquad (13)$$

where P_a - power transmitted,
P_r - power received,
$\tau = \pi R_a R_r/\lambda D$,
R_r - receiving antenna radius

The normalized values of the average power density at the transmitting and receiving antennas are expressed by:

$$W_a = \frac{P_a}{\pi R_a^2\, p_{a\,max}} =$$

$$= 2\sum_{n,m=1}^{N} (x_n x_m + y_n y_m)\cdot B_{nm}, \qquad (14)$$

$$W_r = \frac{P_r}{\pi R_r^2\, p_{r\,max}} =$$

$$= \sum_{n,m=1}^{N} (x_n x_m + y_n y_m)\cdot C_{nm}/(2\,\tau^2 F_{max}^2). \qquad (15)$$

It is convenient to choose the partial amplitude distributions and partial radiation pattern as[12]

$$a_n(\rho) = P_{n-1}(1-2\rho^2),\quad f_n(u) = J_{2n-1}(u)/u \qquad (16)$$

in the case of uniform polarization, where

$P_{n-1}(1-2\rho^2)$ - Legendre polynomials of $n-1$ order,

$J_{2n-1}(u)$ - Bessel functions of $2n-1$ order

and

$$a_n(\rho) = R^1_{2n-1}(\rho),\quad f_n(u) = J_{2n}(u)/u, \qquad (17)$$

in the case of radial polarization, where

$R^1_{2n-1}(\rho)$ - Cernike polynomials of $2n-1$ order,

$J_{2n}(u)$ - Bessel function of $2n$ order.

In this case the values of the coefficients C_{nm} and B_{nm} can be calculated analytically[13]:

$$B_{nm} = 0\ (m \neq n),\ B_{nn} = (4n-2)^{-1} \qquad (18)$$

(uniform),

$$B_{nm} = 0\ (m \neq n),\ B_{nn} = (4n)^{-1} \qquad (19)$$

(radial)

If $m=n$ the recurrent formula can be used:

$$(2\mu+4)C_{n+1,n+1} = 2\mu C_{nn} - J_\mu^2(2\tau) - 2J_{\mu+1}^2(2\tau) - J_{\mu+2}^2(2\tau), \qquad (20)$$

$$C_{11} = (1-J_o^2(2\tau)-J_1^2(2\tau))/2, \qquad (21)$$

(uniform),

$$C_{11} = (1-J_o^2(2\tau)-2J_1^2(2\tau)-J_2^2(2\tau))/4, \qquad (22)$$

(radial)

If $m \neq n$, then

$$C_{nm} = [(\mu-\nu)J_\mu(2\tau)J_\nu(2\tau) + 2\tau J_\mu(2\tau)J_{\nu+1}(2\tau) - 2\tau J_{\mu+1}(2\tau)J_\nu(2\tau)]/(\mu^2-\nu^2), \qquad (23)$$

where $\mu=2n-1$, $\nu=2m-1$ (uniform),
$\mu=2n$, $\nu=2m$ (radial).

Thus the problem of finding the complex function $A(\rho)e^{i\varphi(\rho)}$ has been reduced to the problem of finding the real coefficients x_n and y_n accordingly to the requirements for the SPS characteristics.

The method of penalty functions is the most universal, although rather tedious, method for solving this problem. Making use of nonlinear parametric optimization techniques, it involves finding such values of the coefficients, which provide the minimum of the penalty function whose structure reflects the given problem.

For example, in the problem of maximazing collection efficiency the penalty function is:

$$\phi = 1 - \eta \qquad (24)$$

In the problem of minimizing the electricity cost with constrains for the sidelobe level and maximum value of power density at the antennas the penalty function can be written as:

$$\Phi = -Cost + K_1 u(T_0)(p_{a\,max} - T_0)^2 + K_2 u(I_0)(p_{r\,max} - I_0)^2 + K_3 u(S_0)(p_{s\,max} - S_0)^2 \qquad (25)$$

where $Cost$ - electricity cost,

$p_{a\,max}$, $p_{r\,max}$ - maximum values of power density at the transmitting and receiving antennas,

$p_{s\,max}$ - maximum value of sidelobe power density,

T_0 - transmitting antenna power density limit,

I_0 - receiving antenna power density limit,

S_0 - sidelobe power density limit,

K_1, K_2, K_3 - weighing coefficients,

$u(T_0)$, $u(I_0)$, $u(S_0)$ - unit step functions, where penalties are add only if the limits are violated.

One can use the following formula for the SPS electricity cost[4]:

$$Cost(\text{mills/kWh}) = (9.6 + 22.05\,P_t + 174.4\,R_a^2 + 1.31\,R_r^2)/(P_t\cdot\eta\cdot 0.8), \qquad (26)$$

where P_t - transmit power (GW),

η - collection efficiency,

R_a, R_r - antenna and rectenna radii (km).

Note that in some case (e.g. in the problem of collection efficiency maximization) it is also possible to determine the optimal values of the coefficients in a simpler way - by solving a system of homogeneous linear equations[8,9,14,15].

4. Electricity cost minimization

Arndt et al. studied the problem of synthesis of amplitude distributions at the SPS transmitting antenna with uniformly polarized field[4]. These amplitude distributions minimize the electricity cost while minimizing sidelobe levels to meet 0.01 mW/cm² USSR medical standard.

Making use of the method described above, it is now possible to include the phase distribution into the optimization process and also optimize the characteristics of MPTS with radially polarized field at the antennas.

The penalty function had the form of (25). The optimal values of the expansion coefficients and

antenna radii were found by the Powell method of conjugated directions[11] which requires only the penalty function value to be calculated.

The following values of parameters were used:

- the wavelength λ = 0.12245 m,
- the distance between the antennas D = 36 000 km,
- the power density limit at the transmitting antenna T_0 = 30 kW/m^2,
- the power density limit at the receiving antenna I_0 = 32 mW/cm^2,
- the sidelobe power density limit S_0 = 0.01 mW/cm^2.

The calculation results are given in Fig.7 (uniform polarization) and Fig.8 (radial polarization). The difference between the optimal phase distribution and the quadratic one focusing the beam at the center of the receiving antenna was found to be negligible.

The results obtained indicate that the SPS with radially polarized field at the antennas allows the electricity cost to be reduced to a greater extent as compared with the SPS with uniformly polarized field.

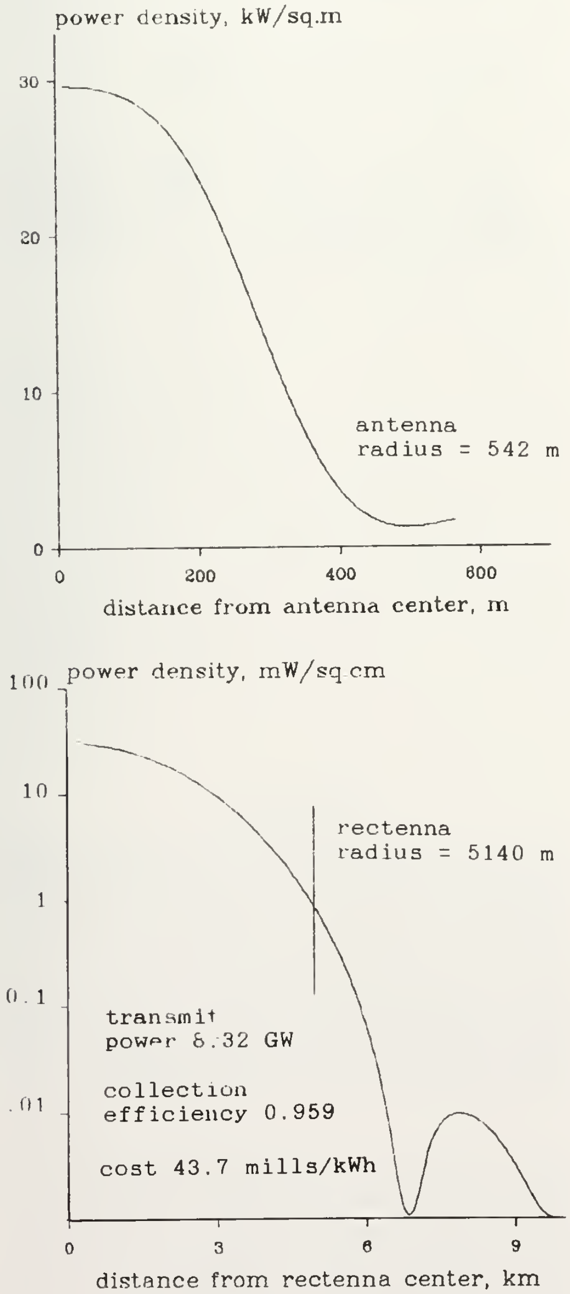

Fig.7
Power density distributions at the transmitting antenna and at the receiving antenna plane, minimizing electricity cost in the case of uniform polarization.

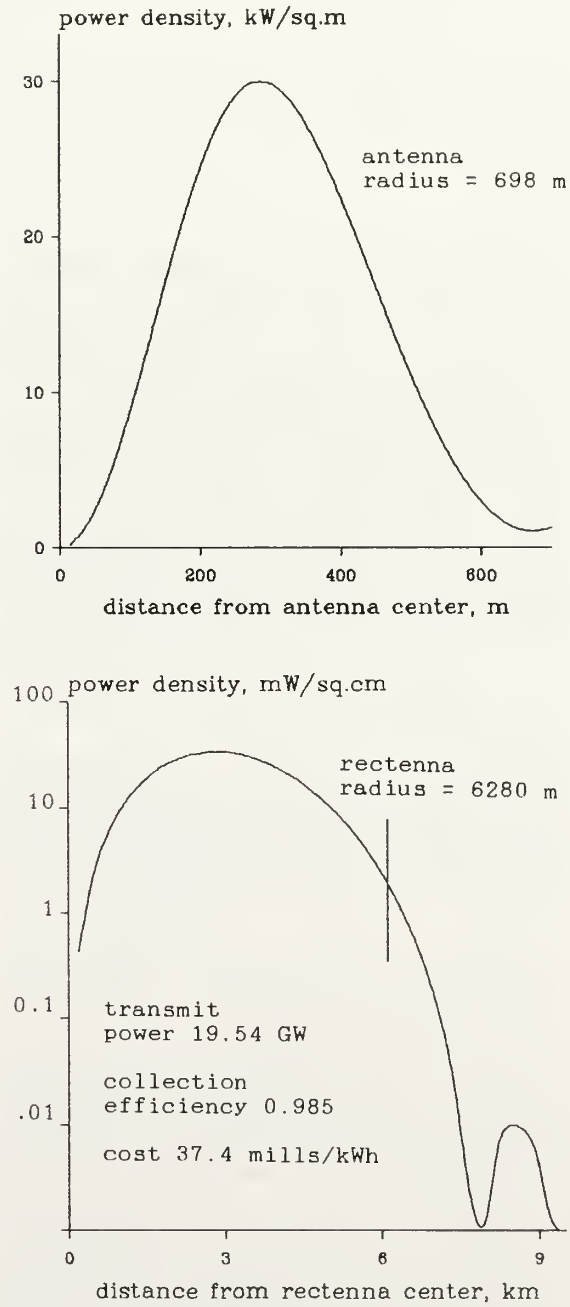

Fig.8
Power density distributions at the transmitting antenna and at the receiving antenna plane, minimizing electricity cost in the case of radial polarization.

5. Conclusions

It is shown that the SPS with radially polarized field at the antennas has a number of advantages over the SPS with uniformly polarized field:

- more power to be transmitted and received at reduced electricity cost ($0.037 per kWh instead $0.044 per kWh for the uniform polarization);
- reduced level of the antenna array diffraction sidelobes;
- elimination of the azimuth angle orientation system;
- improve beam pointing towards the receiving antenna due to using sharp minimum at the beam center.

The microwave power transmission system with radially polarized field at the antennas is also can be more preferable for power transmission between space vehicles, etc.

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B7.5 An inland rectenna using reflector and circular microstrip antennas

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ABSTRACT

A rectenna must have high efficiency of 2.45GHz microwave to DC conversion, and must suppress reradiation of higher harmonic microwave generated by rectifying diodes. A circular microstrip antenna (CMSA) has an important characteristic to reduce the reradiation of higher harmonic microwave. This paper presents an inland rectenna using reflector and CMSAs. The CMSAs are used for a primary radiator (receiving area) of the reflector antenna. The reradiation is reduced by the CMSAs. If the primary radiator is placed at an optimum position, we can have the maximum conversion efficiency of the rectifying diodes. We derive several equations which can be used for the optimum design. Moreover, because the reflector is composed of wires, the rectenna passes the sunshine. Thus, the SPS system does not affect the environment and human society.

RESUME

Une station Rectenna doit présenter un rendement élevé de conversion des microondes à 2.45 GHz en courant continu. En outre elle doit supprimer les réémissions des harmoniques d'ordres élevés produits par les diodes de redressement. Une antenne circulaire de type microstrip a cette caractéristique essentielle de réduire ces réémissions. Le papier présente un système Rectenna, à l'intérieur des terres, utilisant de telles antennes qui sont associées à des réflecteurs. Les antennes microstrip reçoivent l'énergie renvoyée par les réflecteurs et les réémissions sont réduites. Si le récepteur primaire a une position optimum, les diodes de redressement peuvent présenter un rendement de conversion maximum. Nous donnerons plusieurs équations pour préciser cette optimisation. De plus, le réflecteur étant composé de fils, le système Rectenna laisse passer le solcil et par conséquent, n'affecte pas l'environnement et les conditions de vie.

1. Introduction

"Rectenna", the earth station terminal in the solar power satellite (SPS) system converts microwave power transmitted from the SPS into a direct current (DC). The rectenna is one of the essential elements in the SPS system. The rectenna must have high efficiency of energy conversion. Also, it must suppress reradiation of higher harmonic microwave generated by rectifying diodes because the higher harmonic microwave may interfer with radio communications and/or may cause hazards to human body.

In this paper, we give an outline of a circular microstrip antenna (CMSA) which has been proposed to use for a rectenna by the authors. The CMSA in itself reduces the reradiation of higher harmonic microwave. Next, we propose the rectenna using a reflector with wires and a primary radiator (receiving area) with CMSAs. We show fundamental expressions which will be useful for designing the rectenna. Since the rectenna passes the sunshine, it dose not affect the environment and human society. Then, we introduce the rectenna in the SPS strawman model which has been discussed in the Institute of Space and Astoronautical Science (ISAS), Japan. Moreover, we compare the inland rectenna and offshore one, and we show that the inland rectenna has the advantage over the offshore one.

2. Circular Microstrip Antenna (CMSA)

Mainly, a half-wavelength dipole antenna has been investigated for the rectena.[1] However, the dipole antenna reradiates a considerable amount of higher harmonic microwave generated by the rectifing diodes, and a low-pass filter must reduce the higher harmonic components drastically. The authors have proposed the rectenna composed of the CMSA shown in Fig.1.[2,3] Microstrip antennas have several attractive properties, namely they are low in profile, light in weight, compact and conformable in structure, easy to fabricate, easily integrated with solid-state devices, and easy to adapt to the photoetching technique in fabrication.

The eigenvalues of CMSA are given by the following equation :

$$J'_n(ka) = 0 \tag{1}$$

$$k = 2\pi f_r \sqrt{\varepsilon_r \varepsilon_0 \mu_0} \tag{2}$$

$J_n(x)$: the Bessel function of the first kind and order n
a : radius of the circular patch
f_r : resonant frequency
ε_r : specific dielectric constant of substrate.

The radiation characteristics of the CMSA are depicted in Fig.2. We can see that a higher resonance-harmonic frequency is not an integer multiple of the dominant resonance frequency ($f_0 = 2.45$ GHz) . Thus, the CMSA can reduce the reradiation of higher harmonic microwave. Furthermore, if we cut slits on the CMSA as shown in Fig.3 where directions of the slits coincide with the ones of current flow for the dominant mode (TM_{110}) , we can suppress TM_{010} and TM_{120} modes. The resonant frequencies of the TM_{010} and TM_{120} modes are $2.08 f_0$ and $2.9 f_0$, respectively. Then, we can reduce the reradiation of $2f_0$ and $3f_0$ more effectively.

Fig.4 shows radiation patterns of the CMAS at the frequency of 2.45 GHz. They were calculated assuming that the CMSA is on an infinite ground plane. We can see from Fig.4 that the CMSA has a broad beam on both of the E-plane and H-plane.

The CMSA has several advantages for the rectenna as shown above. However, if we compose the rectenna from the CMSA, it intercepts the sunshine. This is not preferred for the environment, human activities and industry.

3. Rectenna composed of reflector and CMSA

In this section, we describe the rectenna which receives the microwave from the SPS and passes the sunshine. The rectenna is composed of a reflector with wires and a primary radiator (receiving area) with CMSAs. Because the wires are used for the reflector, the rectenna is almost transparent. Thus, the SPS system does not affect the environment, industry and human society. Moreover, since the primary radiator is composed of the CMSAs, we can reduce the reradiation of higher harmonic microwave. We discuss parabolic type and hogline type reflectors in the following. Especially, we describe the former in detail.

3.1 Parabolic rectenna

Fig.5 shows the rectenna with an offset parabolic reflector. Since the reflector is cylinder parabolic, the microwave from the SPS is reflected in such a way that the microwave concentrates on a focal line.

For the sake of convenience, we consider the characteristics assuming that the reflector is composed of a metal sheet. Fig.6 shows a cross section of the rectenna using the cylinder parabolic reflector. The reflector is the offset parabola of focal length f. The focal line is shown by F. The elevation angle of the SPS is θ_s.

The rectifying diodes might be damaged if we place them on the focal line (F) , because the microwave power density is too large. If we place the primary radiator off focus as shown in Fig.6, we can lower the microwave power density below the damage level. Moreover, choosing optimum D_a , we can have a maximum value of RF to DC energy conversion efficiency of the diodes.

Let us denote the length of arc primary radiator by D_d as shown in Fig.6. Then, we have the following equations.

$$D = D_a \sin\theta_s \tag{3}$$

$$D_d = \frac{1}{\sin\theta_s}(2f\sin\theta_s - D_a)\left\{\frac{\pi}{2} - 2\tan^{-1}\left(1 - \frac{D_a \sin\theta_s}{2f}\right)\right\} \tag{4}$$

From these equations, D/D_d can be given by

$$\frac{D}{D_d} = \frac{D_a \sin^2\theta_s}{(2f\sin\theta_s - D_a)\left\{\frac{\pi}{2} - 2\tan^{-1}\left(1 - \frac{D_a\sin\theta_s}{2f}\right)\right\}}. \tag{5}$$

We can see that D/D_d indicates the concentration of the incident microwave power.

Fig.7 shows the power concentration (D/D_d) as a function of D_a/f for several values of θ_s. From Fig.7, we can obtain the optimum D_a which maximizes the energy conversion efficiency of the rectifying diodes.

Fig.8 shows the cross section of the rectenna site using the cylinder parabolic reflectors. The primary radiator is placed on the back of the prop which supports the reflector.

Fig.9 shows the cross section of the rectenna using the plane primary radiator. The power concentration (D/D_d) can be obtained in the same manner mentioned previously and is given by

$$\frac{D}{D_d} = \frac{D_a \sin^2\theta_s}{2\,(2f\sin\theta_s - D_a)\sin\left\{\frac{\pi}{4} - \tan^{-1}\left(1 - \frac{D_a\sin\theta_s}{2f}\right)\right\}}. \tag{6}$$

Fig.10 shows the power concentration D/D_d versus D_a/f for the rectenna shown in Fig.9. We can obtain the optimum value of D_a which maximizes energy conversion efficiency.

We arrange plural CMSAs lengthwise depending on D_d as shown in Fig.5. On the plane containing the focal line, we have a radiation pattern which is the same as the E-plane pattern of the CMSA shown in Fig.4(a). Namely, the beam on the plane is very broad. On the plane perpendicular to the focal line, we have the radiation pattern which is determined by the reflector and the number of lengthwise CMSAs. The more CMSAs are arranged lengthwise, the broader the beam is, namely the allowance of the inclination angle of the SPS becomes large.

The rectenna site is constructed on the equator in the SPS strawman model which will be mentioned later, and the elevation angle θ_s is 90°. In this case, we can compose the rectenna as shown in Fig.11 from the two rectennas shown in Fig.6. It is desired to place the CMSAs also on the upper side of the primary radiator. The rectenna will be supported by props on the jungle in the SPS strawman model. The symmetrical structure shown in Fig.11 is desirable because it is easy to keep the balance.

3.2 Hogline rectenna[4]

Fig.12 shows the hogline rectenna. This is considered to be a horn reflector antenna, and the reflector and horn are composed of the wires in a similar manner as the parabolic rectenna. The hogline rectenna receives the microwave from the SPS and passes the sunshine.

We must determine which type of the rectenna should be chosen from careful considerations of the performance, cost and ease of construction.

4. Inland rectenna

The rectenna is constructed either inland or offshore. From the view point of energy transmission, the inland rectenna has the advantage over the offshore one. Furthermore the offshore rectenna is not preferable since it must take measures to cope with salt damage, icing and sea birds.[5]

The strawman model is an experimental version of the SPS system which has been discussed by the ISAS SPS Working Group. The SPS will be built in a low altitude (about 1,000km) equatorial orbit. The rectenna site is constructed in a developing country on the equator. Only when the SPS passes above the rectenna site, the energy transmission experiment is carried out. Since the SPS of the strawman model orbits about the earth from west to east, the rectenna should have a broad beam in the east and west direction. The rectenna composed of the reflector and CMSAs has a broad beam on the plane containing the focal line as mentioned previously. Then, we should place the focal line in parallel with east and west direction. The rectenna is sited on the jungle in the developing country. Because the rectenna passes the sunshine, the experiment does not affect the ecology of the jungle.

In the SPS system for practical use, the rectennas will be sited mainly in advanced countries. We may construct an artificial city under the rectenna. The diameter of the rectenna is about 10km, and the urban area is about 64km^2 inside the rectenna. Moreover, we may construct an international airport with six runways around the rectenna as shown in Fig.13. A great deal of electric power will provide us the livable environment in the city.

5. Conclusions

We have described the concept of rectenna with the reflector and CMSAs. The rectenna receives the microwave from the SPS with high efficiency, and passes the sunshine. Thus, the rectenna does not affect the environment and human society. Moreover, the rectenna proposed in this paper can be used also for the strawman model discussed by the ISAS SPS Working Group.

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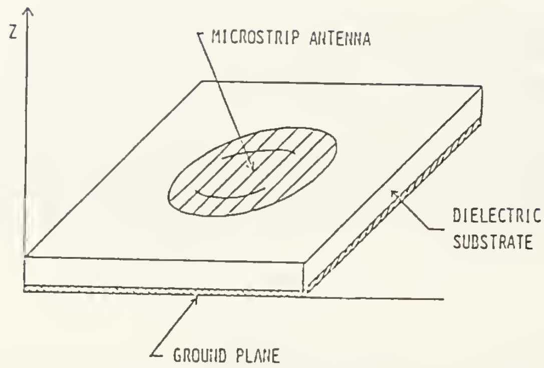

Fig.1

General geometry of a circular microstrip antenna.

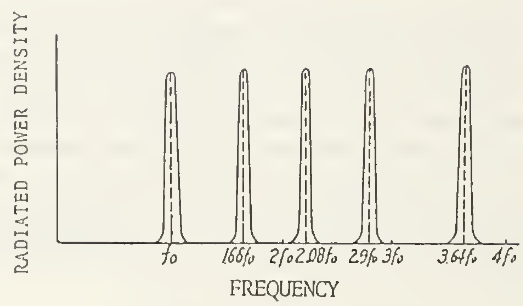

Fig.2

Radiation characteristics of the CMSA.

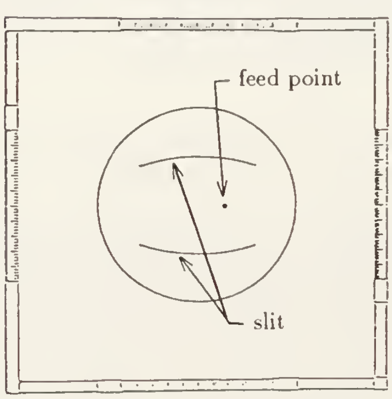

Fig.3

Geometry of the CMSA with slits.

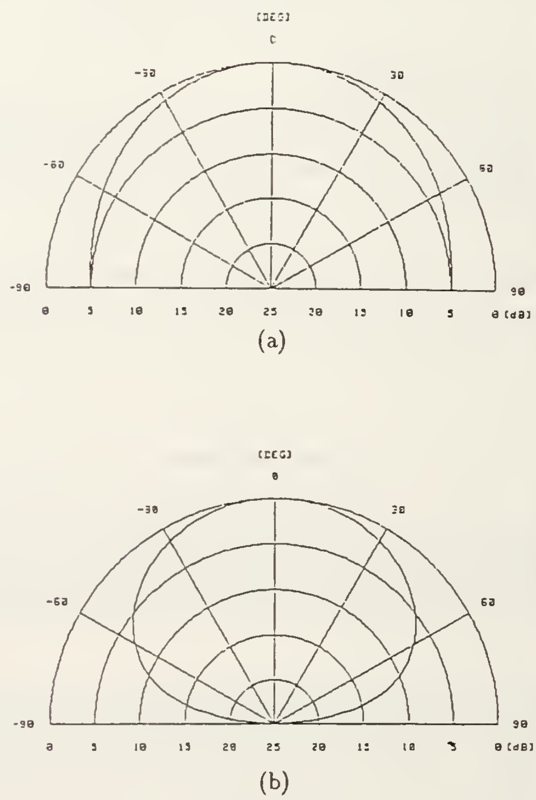

Fig.4

Radiation patterns of the CMSA at the dominant frequency (2.45GHz). (a) E-plane (b) H-plane.

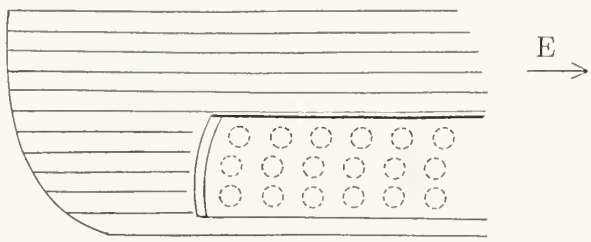

Fig.5

Offset parabolic reflector rectenna with the CMSAs. The CMSAs illustrated by the dotted line are placed on the side of the reflector.

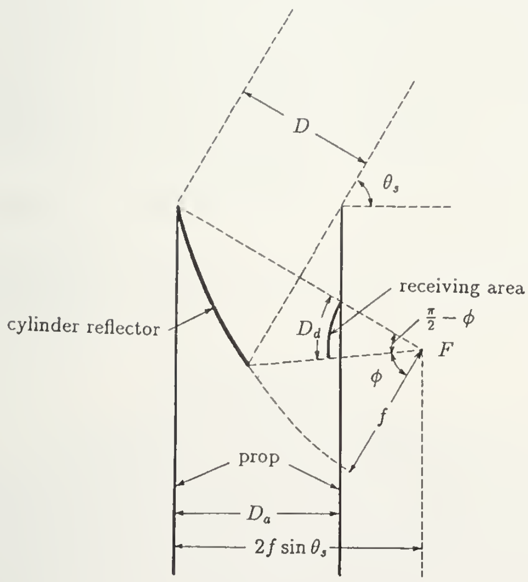

Fig.6

Cross section of the offset parablic reflector rectenna (1).

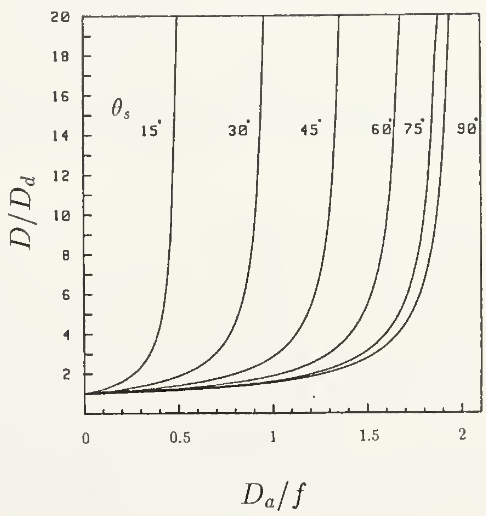

Fig.7

D/D_d versus D_a/f for the rectenna shown in Fig.6.

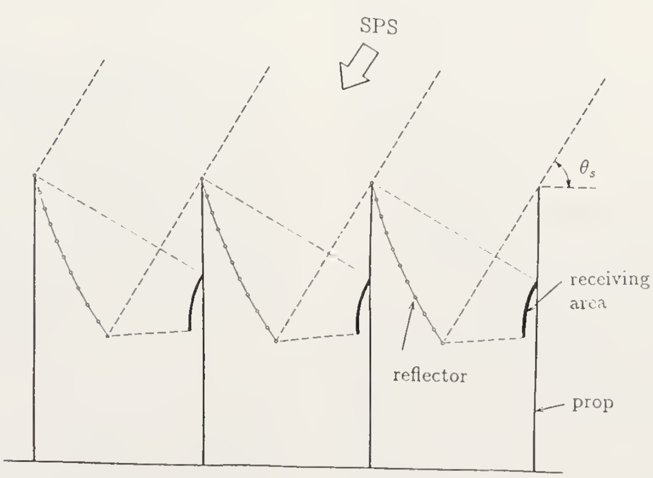

Fig.8

Cross section of the rectenna site.

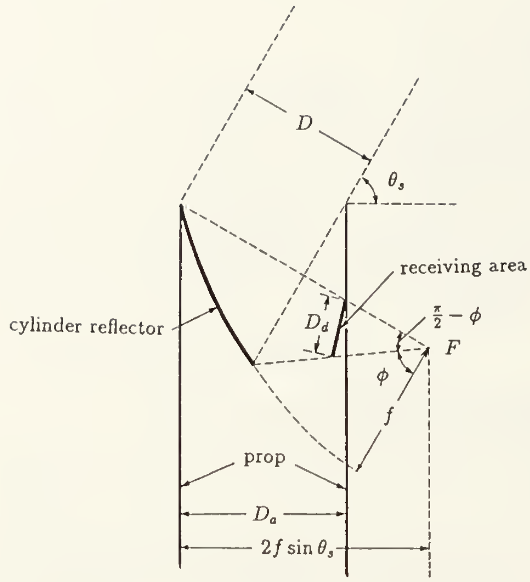

Fig.9

Cross section of the offset parabolic reflector rectenna (2). The primary radiators are placed ona plane.

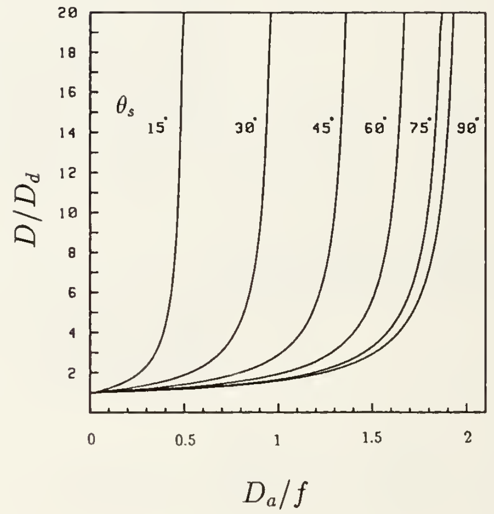

Fig.10

D/D_d versus D_a/f for the rectenna shown in Fig.9.

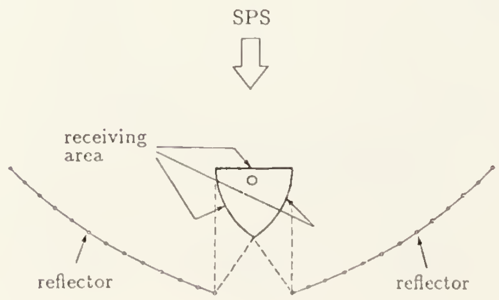

Fig.11

The resctenna on the equator.

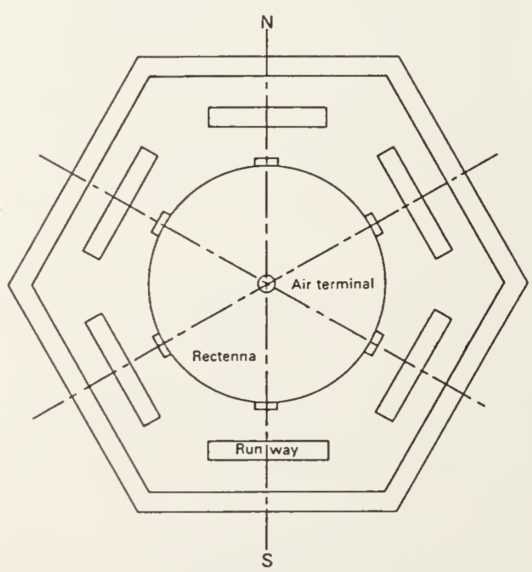

Fig.13

Inland rectenna and international airpot city.

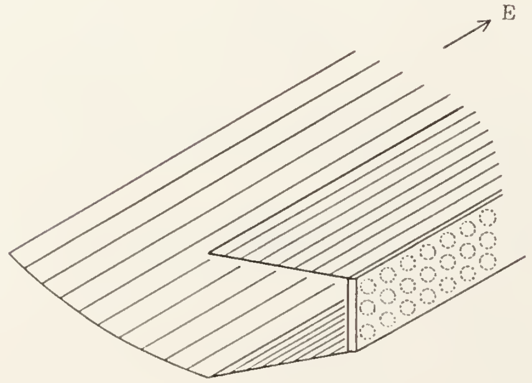

Fig.12

Hogline rectenna with the CMSAs. The CMSAs illustrated by the dotted line are placed on the side of the reflector.

B8.1 35 and 94 GHz rectifying antenna systems

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Abstract

This paper reports on the design and development of rectennas (rectifying antennas) and associated power beaming systems at 35 GHz and higher. The paper includes discussion on the history of power beaming, the advantages of high frequency systems, the advancement of millimeter wave rectenna technology, and possible space and terrestrial applications.

Résumé

Cet article rapporte sur la conception et le développement des «rectennas» (antennes-redresseurs) et de ses systèmes de transmission d'energie à fréquences de 35 GHz et superieurs. L'article discute l'histoire de la transmission d'energie par micro-ondes, les avantages des systèmes à fréquences superieurs, l'avancement de la technologie des rectennas pour ondes millimetrique, et des applications possibles dans l'espace et sur la terre.

Introduction

The idea of power transmission at microwave frequencies was first introduced by Dr. W.C. Brown in the 1960's. Under NASA funding, Dr. Brown led the pioneering research effort and demonstrated an S-Band (2.45 GHz) power beamed helicopter platform in 1964. Since then, Dr. Brown's excellent work has continued to improve his systems, achieving extremely high system efficiencies at 2.45 GHz[1].

In 1968, Dr. P. Glaser launched his work on the Solar Powered Satellite (SPS) which involved the design of large solar powered satellites that converted solar energy to RF and beamed it to large 2.45 GHz rectennas on earth. Research on the SPS concept continued through the 1970s. That work included a demonstration at Goldstone in 1975 in which 30 kW were beamed a distance of one mile.

In the last ten years, the Canadian Stationary High-Altitude Relay Platform (SHARP) program has progressed with the development of an S-band system which powers a small airplane at low altitude. The SHARP program is continuing with a goal of producing a high altitude aircraft powered by microwave energy. NASA continued work on power beaming, broadening its focus from aircraft to include space applications. It was recognized that higher frequencies would greatly improve the cost effectiveness of power beaming and the development of the gyrotron as a high power, high frequency RF source in the 1980s provided a practical power source at 35 GHz and higher. Work on rectennas, however, remained in the vicinity of 2.45 GHz and showed no sign of making the jump to much higher frequency. In 1987 APTI undertook an effort to develop a working rectenna and to design a power beaming system in the Ka band. This program has been extremely successful and has resulted in a scalable rectenna design that operates at 35 GHz and higher frequencies.

Millimeter Wave Rectenna Technology

Advancing the rectenna technology into the millimeter wave region isn't a recent phenomena. Dr. Brown conducted a study into developing a network at 20 GHz in the 1980s[6]. There are, however, several obstacles to overcome as the operating frequency is increased. Almost all rectennas developed to date incorporate the printed-circuit technology in their design. Both Brown's and the Canadian S-band rectennas have been fabricated by such

means, and efficiencies of over 70% have been achieved by both. At higher frequencies, however, the printed-circuit approach has drawbacks, the greatest of which is power loss. For instance, previous works with microstrips at millimeter wavelengths have shown as much as 0.5 dB/inch loss (35 GHz).[3] There are also concerns with reduced power handling capability, fabrication tolerances, and cost of the high frequency diodes. Hence, simply scaling the working S-band design to a higher frequency may not be sufficient; a new approach may be needed. The newly developed receiving antenna and rectifying circuit structure [US Patent pending] overcomes several problems associated with millimeter wave rectenna operation. Figure 1 shows the outer surface of an array of such rectennas. The most salient feature of this rectenna is the increased power reception (due to an enhanced resonant structure) without any significant increase in total weight (i.e., as compared to a multi-layer structure). This design also incorporates a solution to the problem of thermal management. The network was realized in such a way that the placement of the diode allows the use of the outer layer as an effective radiator. This would permit operation at high power densities (approaching 1 W/cm^2). The metal clad substrate is also used to isolate the semiconducting devices from over-voltage conditions in space applications. The antenna and the rectifying network lie underneath this protective layer. The rectenna circuits were fabricated on low dielectic boards using off-the-shelf GaAs diodes. These Schottky-barrier diodes have series resistance (Rs) of less than 4 ohms, junction capacitance (Cjo) of 0.07 picofarads, reverse breakdown voltage (Vbr) of 6 volts, and power dissipation capability of about 50 milliwatts. Several circuits were tested using a solid state oscillator and a traveling wave tube amplifier. The results have been plotted in Figure 2. The graph also includes expected rectenna performances for two cases: with and without the input filter. The theoretical curves were obtained running a circuit simulation code (such as SPICE) on a simple circuit model (Figure 3).

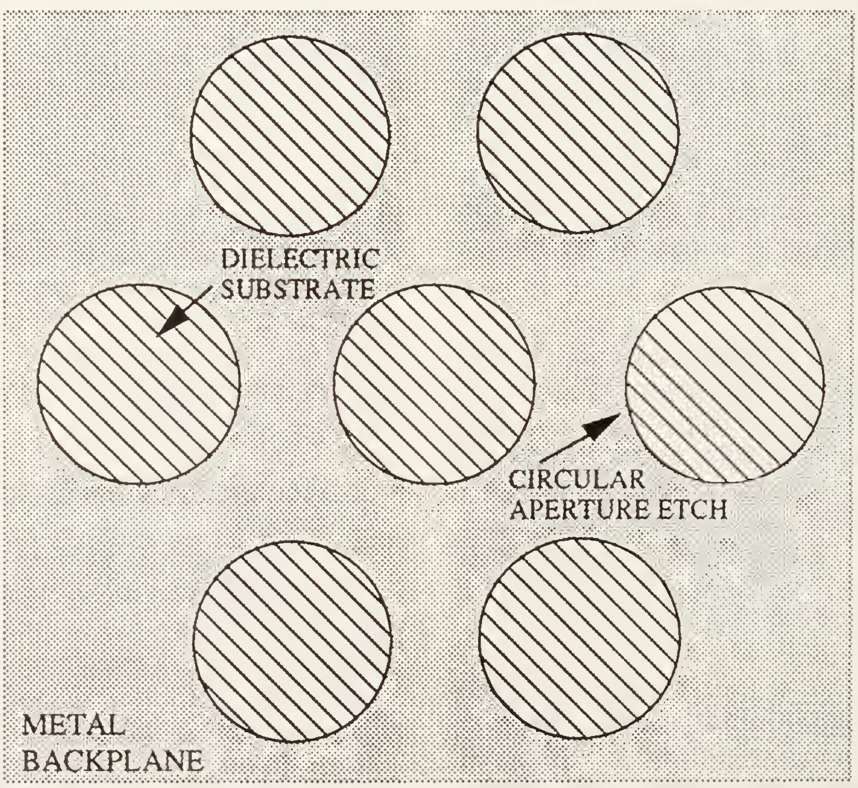


Figure 1. Outer Surface of the Rectenna Panel

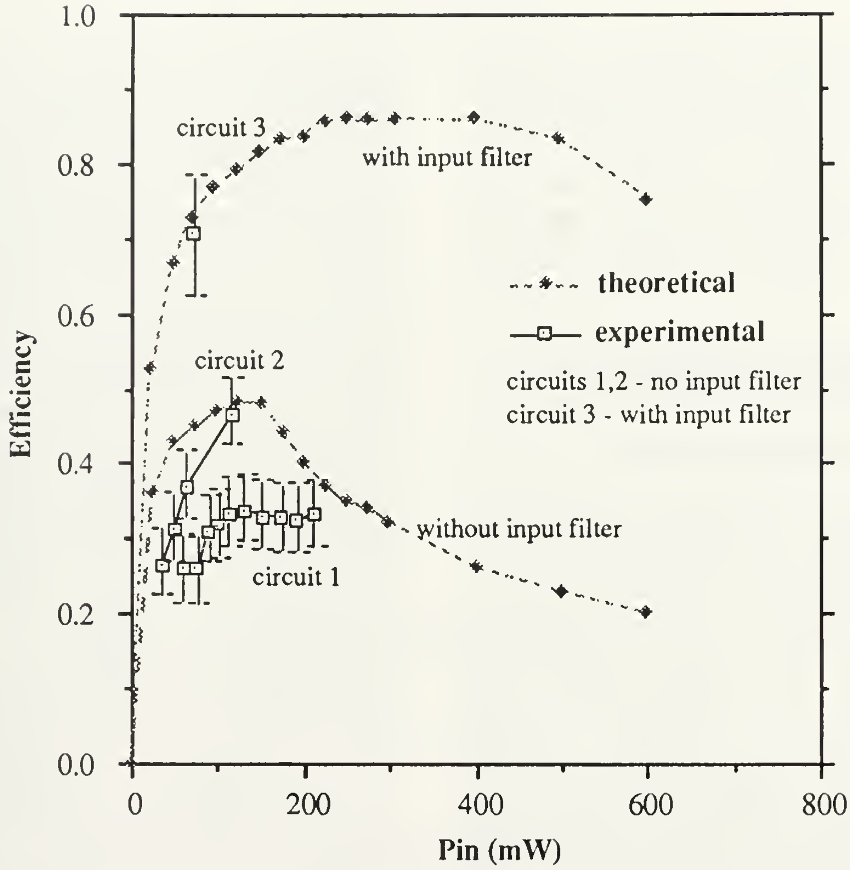


Figure 2. Theoretical Performance and Experimental Results

The experimental results show that a 70% efficient rectenna at 35 GHz is possible. It should be noted that circuits 1 & 2 have been fabricated without the input filters because of tight tolerance conditions, which are restricted by the current etching technology. (It has been our aim to relax the etching tolerances at this stage by omitting the input filter. The final network, however, will include input filters.) It should also be noted that not all of the unconverted RF power is dissipated in the diode. In the case of the 70% efficient rectenna, for instance, it has been calculated that 5-10% is dissipated as heat in the structure and the balance is reflected. Future work will include high power density tests to confirm the simulation results. An infrared radiometer may be used to monitor the diode power dissipation. The present rectenna structure operates at Ka-band, but the same approach can be used to fabricate

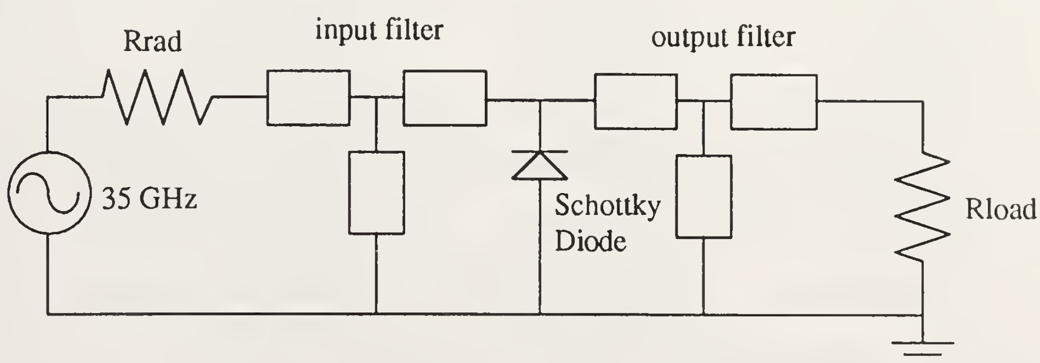


Figure 3. Rectenna Circuit Model

networks to operate at higher or lower frequencies. Plans have been made to develop both a hybrid and MMIC rectenna at W-band. 94 GHz hybrid rectennas have been fabricated and tested. Preliminary tests indicate low efficiency RF to DC conversion. This effort, however, is still in its embryonic stage, and further work is required to properly evaluate circuit performance.

Power Beaming at Millimeter and Submillimeter Wavelengths

The Reasons for Being at 35 GHz

The major reason for operating a microwave power beaming system at high frequency is the scaled reduction in antenna size. For a given rectenna panel size, the transmitting antenna at 35 GHz is more than ten times smaller than at 2.45 GHz. This is a significant issue for systems designed to beam hundreds of kilowatts or even megawatts of power. For instance, a power beaming system designed for space to ground application requiring distances of up to 100 kilometers and given a 20 meter diameter rectenna panel would need a 780 meter diameter transmitter at 2.45 GHz, a 54 meter diameter unit at 35 GHz, and a 20 meter unit at 94 GHz. Or for space to space application with a range of up to 20 kilometer and 12 meter diameter rectenna panel, a 204 meter diameter transmitter will be needed at 2.45 GHz, a 14.3 meter diameter unit at 35 GHz, and a 1.7 meter unit at 300 GHz. For the latter application, it can easily be seen that at Ka-band and above, the transmitting antenna can be a single parabolic dish on a pedestal - a more manageable system than an array of smaller units at S-band.

The difficulties and disadvantages at higher frequencies do exist, but are not insurmountable. For instance, until recently obtaining hundreds of kilowatts of power with a single source at millimeter wave frequencies was near impossible. This barrier was overcome with the advent of a new class of oscillators known as gyro-devices, where the cyclotron resonator replaces the physical resonator as in conventional tubes. The gyrotron, which falls into this category, is a microwave vacuum tube operating on the principle of interaction between an electron beam and microwave fields. Coupling is achieved by the cyclotron resonance condition, which permits the beam and microwave circuit dimensions to be large compared to a wavelength. This unique feature circumvents the power density problem encountered in conventional klystrons and travelling wave tubes at millimeter wavelengths. Gyrotrons capable of generating 200 kilowatts CW at 35 GHz have been built and are currently being used by various groups. And technologies exist for the development of high power gyro-devices capable of delivering even greater power at millimeter and submillimeter wavelengths. Table 1 shows gyro-devices available (or under development) at various frequencies.

FREQUENCY	TUBE TYPE & PERFORMANCE	
35 GHz	GYROTRON -	200 kW CW
94 GHz	GYRO-TWT -	100 kW CW
110 GHz	GYRO-TWT -	500 kW pulsed
140 GHz	GYROTRON -	400 kW CW (1 MW CW unit under development)
160 GHz	GYROTRON -	500 kW pulsed unit under development
280 GHz	GYROTRON -	1MW CW unit under development
100-300 GHz	QUASI-OPTICAL - GYROTRON	1 MW CW unit under development

Table 1. Gyro-Device at Millimeter and Submillimeter Wavelengths

Advances in manufacturing transmitting antennas have also contributed to the feasibility of high frequency power beaming. A 20 meter parabolic dish with a tracking antenna mounted on a pedestal and capable of two arc seconds rms (each axis) tracking accuracy is available from the industry.[4] There is also the issue of increased atmospheric absorption of millimeter waves, but windows do exist at 35 GHz, 94 GHz and other discrete frequencies. Figure 3 is a plot of atmospheric attenuation versus frequency[7]. Although the chart indicates attenuation for horizontal passage, atmospheric attenuation in general decreases with increasing altitude. For instance, the total attenuation of a 35 GHz beam in traversing vertically through the atmosphere in clear weather is approximately 0.2 dB. As for the diode, off-the-shelf GaAs Schottky-barrier diodes can be used at moderate power densities (2 kW/m^2). However, for densities approaching 1 W/cm^2, development of a new type of high power diode may be required. Such a specification has been established during the course of rectenna developmental work. Figure 5 is a comparison between the conventional and the proposed high power Schottky diode. Recent evaluation of the GaAs diode technology has revealed that capabilities exist for fabricating such diodes in large quantities at a moderate cost.

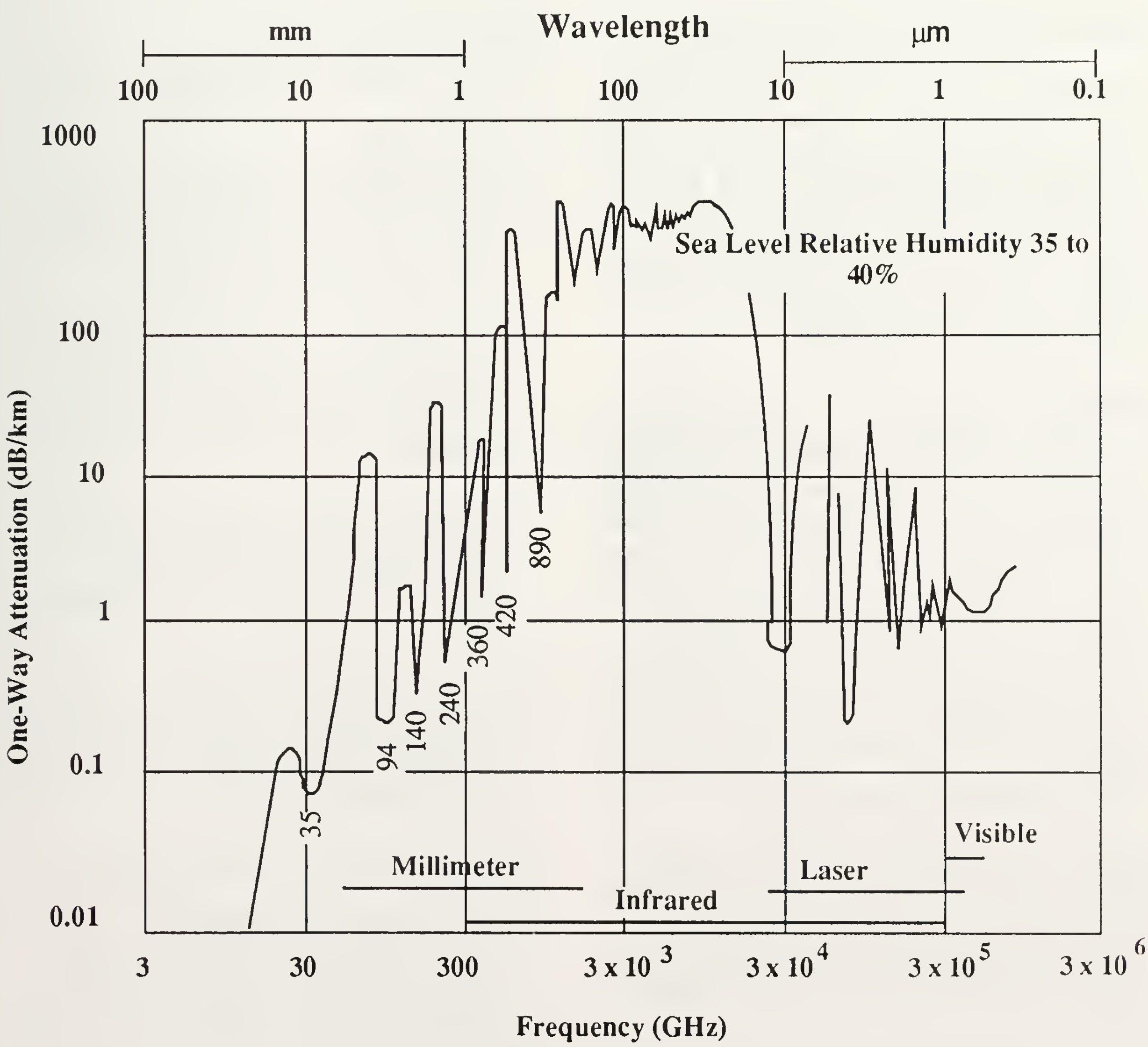
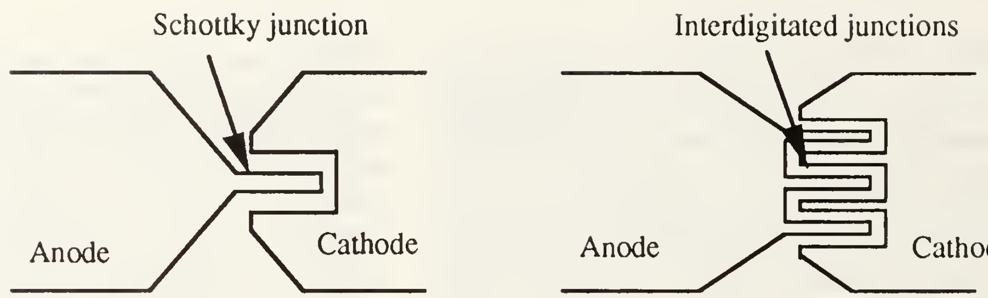


Figure 4. Atmospheric Attenuation vs. Frequency



Typical Schottky-barrier Diode

Is	=	100 pA
Rs	=	4 Ohms
Cjo	=	0.07 pF
Vbr	=	6 V

Proposed High Power Schottky Diode

Is	>	1 nA
Rs	<	2 Ohms
Cjo	<	0.1 pF
Vbr	>	10 V

Figure 5. Millimeter Wave Schottky Diodes

<u>Space-to-Space Power Beaming System</u>

It may be helpful at this point to study a 35 GHz power beaming system operating in space. Consider a space-to-space power beaming system which includes a power (solar) station and one or more remotely powered satellites. The solar power station contains a high power RF source (for instance, a gyrotron), high gain antenna to beam the power, and a tracking and control unit to oversee the operation. Figure 6 shows a proposed system layout.

<u>Space Power Station</u> - The power is supplied to the remote satellite(s) via a microwave (35 GHz) beam transmitted from a dish antenna. The antenna size is dependent upon the satellite location, size, and system efficiency requirement, but could range from 3 to 15 meters in diameter. Power is supplied by the prime power unit (solar), and converted to RF by a gyrotron. A high tolerance Cassegrain reflector antenna is used to beam the power to the satellite and to track the satellitie. The tracking will be accomplished using a satellite beacon at a lower frequency (e.g. X-Band). The power station will use many off-the-shelf components.

<u>Satellite</u> - The satellite is attached to a planar structure which will be covered by a conformal rectenna that converts the RF to DC. This rectenna consists of panels of antenna elements and operates at an efficiency of approximately 80%.

Other applications of power beaming would include space-to-lunar and space-to-Mars as well as space-to-earth systems.

<u>ACKNOWLEDGMENTS</u>

The authors wish to acknowledge valuable contributions from W. Milner and T. Wallace.

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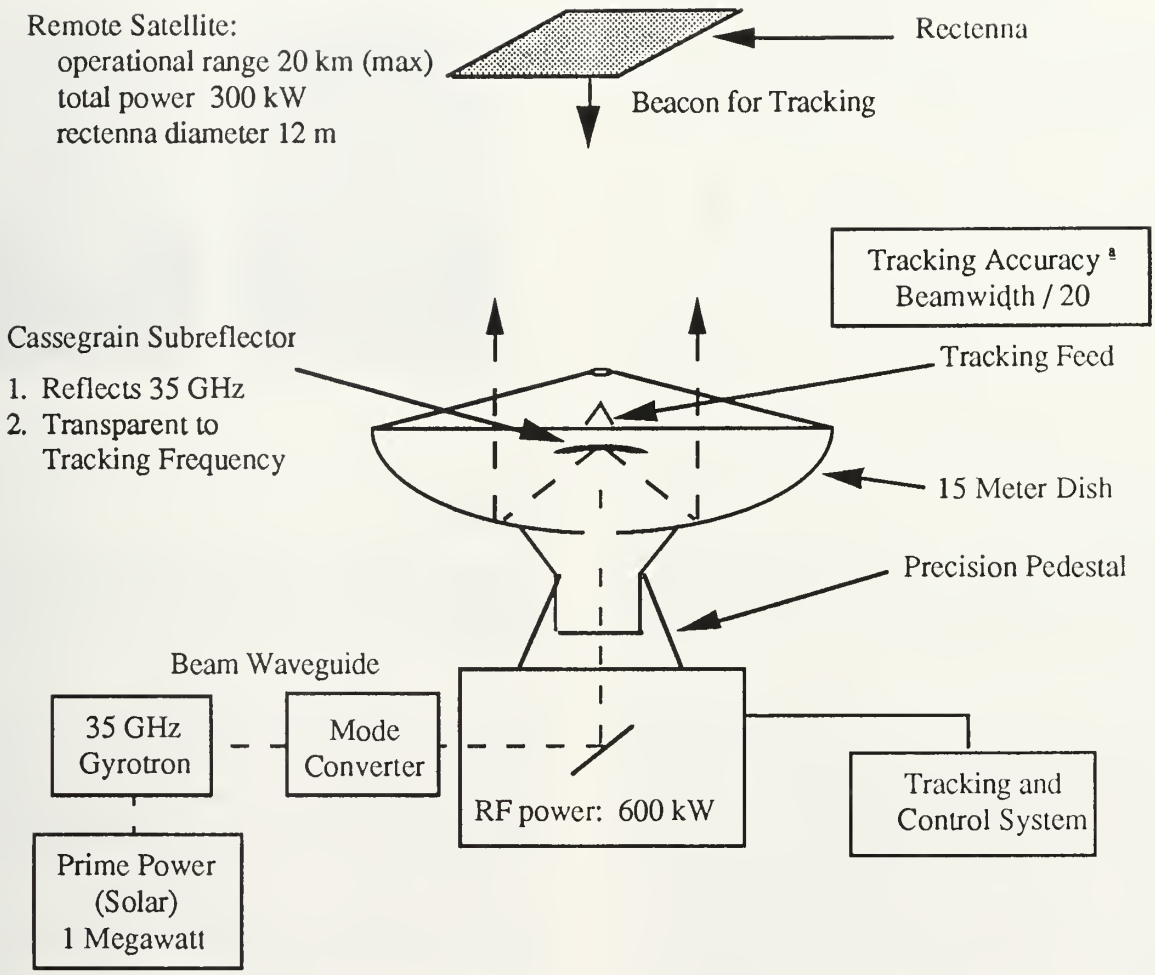

Figure 6. Illustrative Space-to-Space Power Beaming System

B8.2 Frequency range analysis for power transmission by electromagnetic beam

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ABSTRACT

This paper analyses the problem of determination of frequency range for power transmission by electromagnetic beam in case of power transmission through Earth's atmosphere.

RESUME

Cet article analyse le problème de la détermination des fréquences auxquelles l'énergie électromagnétique sera émise, dans le cas de transmission à travers l'atmosphère terrestre.

The interest arisen in last time for the possibility to use the electromagnetic radiation not only as a means of the information transmission but also as one of way of the power transportation, is due to a number of causes which are, fist of all, the successes in the field of generation and transmission of high-energy bundles of electromagnetic power by means of a beam, and also - the appearance of essentially new possibility for solving a number of technical problems - both existing at present and also envisaged in advanced programs-in case of the practical realization such methods of power obtaining and transmitting. The possible problems, in solution of which the use of electromagnetic radiation seems to be very promising, includes: the use of electromagnetic radiation in different industrial technological processes connected with heating and special treatment of different materials, e.g.,in the food industry, in the chemical industry for intensifying the course of chemical reaction; in the medicine, in different physical investigations up to the experiments in the field of thermonuclear synthesis, in the projects concerning the creation of transport means based on quite new principles, and in solving other problems. From all this variety of such problems we single out only those for which it is not possible to obtain the solutions with any other methods without using the energy of electromagnetic radiation.

To such problems of microwave energetics belong different projects of the use of space energy on the Earth and an inverse problem connected with the energy transmission from the Earth to the board of spacecraft. Moreover, this is the problems of energy transmission from one spacecraft to another, the project of power transportation between two distant regions of Earth using an orbital reflector, and a number of other analogous problems.

It is obvious that the solution of such problems is a very complex scientific-technical problem, the successful solution of which depends on great number of factors. One of this factor is the correct choice of frequency of the electromagnetic radiation used for the power transmission by means of a beam. Analyzing the possible frequency range and choosing a working frequency of electromagnetic radiation, as applied to the listed above problems, it is expedient to single put two groups of problems, namely, the problem, the solution of which requires the power transmission under condition of space, and the problems in which the power is transmitted through the Earth's atmosphere by means of an electromagnetic beam.

In this report, we limit ourselves to the consideration of second group of problems. It is obvious that the choice of electromagnetic radiation working frequency depends on a number of factors. However, first of all, the nature of the beam - atmosphere interaction and the processes of electromagnetic radiation propagation in the Earth's atmosphere must be taken into account. From the analysis of above processes and the comparison of corresponding characteristics - microwave and optical - it follows: the radiation of optical frequency range is very intensively absorbed in the Earth's atmosphere and this type of radiation is more expedient to use for the energy transmission in space. In the problems of energy transmission through the atmosphere it is preferable to use microwave radiation. As is already noted, the problem, raised in analysis of possible frequency for the transmission of energy by means of a electromagnetic beam, is a multiparameter problem, the solution of which depends first of all in the choice of the optimality criterion. Not pretending to solve completely the problem, attempt will be made to determine the way of its solution, to analyze the effect of different factors on the final result.

Taking into account that at present and in the near perspective, the generally accepted criterion in the estimation of all aerospace projects is the possibility of achievement of minimum mass and size characteristics of spacecraft for the fulfilment of the prescribed flight program, we also would follow this criterion.

The choice of microwave range for the power transmission by means of a electromagnetic beam is conditioned by the fact that in the radiofrequency range of electromagnetic waves, the microwaves can be focused in a best way compared with more long-wave range. Naturally, this focusing capacity make microwave radiation the most attractive for the purposes of directed power transmission by means of electro-

magnetic beam. It is know that just the microwave frequency range is proposed for using in the energy transfer from a stationary orbit to the Earth's surface in the projects of solar and nuclear orbital power stations when choosing the frequencies from 2.5 GHz to 3 GHz. These frequencies correspond to the requirement for above projects, namely: weak influence of the Earth's atmosphere on the process of electromagnetic beam propagation and good technical support from the standpoint of both generation and focusing of radiation. In this case, it is assumed that the ground receiving antenna have the diameter equal to 10 km and the diameter of orbiting transmitting antenna equals 1 km.

Let us investigate the possible microwave frequency range for the energy transmission by means of a microwave beam through the Earth's atmosphere for all problems of such type, exemplified by the existing projects of orbital power station for ground power supply. The examination of mass and size characteristics of above-mentioned projects, depending on the concrete elaborations, shows that the mass of transmitting orbital antenna in the projects of solar orbital power stations varies from 15% to 30% of total mass of the orbital power station. In the projects of nuclear orbital power stations the same parameter equals 15% - 40% of total mass. The dimensions (and correspondingly mass) of orbital antenna were chosen taking into account the fact that at prescribed size of the ground receiving antenna, altitude of stationary orbit, and working length of electromagnetic wave of the order of 10 cm, the transmitting antenna must have the diameter of the order of 1 km for providing the efficiency of energy transfer between two antennas close to 100%, supposing the absence of losses on the way of microwave beam passing through the Earth's atmosphere. Such a high coefficient of energy transmission from an orbital antenna to a ground antenna is realized at the fulfilment of condition:

$$\tau = \sqrt{A_t * A_2} / \lambda * L \geqslant 2.4$$

where:

τ - dimensionless parameter influencing the efficiency of receiving-transmitting antennas;

A_t, A_2 - areas of transmitting and receiving antennas respectively;

λ - wave length of microwave radiation;

L - distance between antennas (orbit height).

Taking into account the fact that the size of receiving ground antenna is determined by the ecologically safe level of the microwave density near the Earth's surface at prescribed total radiation energy of orbital power station, it is worth-while to suppose - in performing further examination - that the diameter of ground antenna is maintained equal to 10 km.

For maintaining a high efficiency of the receiving-transmitting antennas without taking into account the losses in the Earth's atmosphere, it is necessary to fulfil the condition $\tau \geqslant 2.4$. At fixed values of the parameters A_2 and L, the decrease of transmitting antenna size is possible only at the expense of increasing the microwave radiation frequency, i.e., at the expense of the value of λ. It is obvious that the increase of frequency of microwave signal used is possible only taking into account all variety of the processes of interaction between the electromagnetic radiation and the Earth's atmosphere, and accounting for all losses accompanying the process of energy transmission from the stationary orbit to the Earth using microwave beam. The interaction of microwave radiation with the Earth's atmosphere is a complex and multiform process including the signal decay due to the radiation absorption by the oxygen molecules and water vapor, the dispersion of waves in the presence of rain, mist, cloudiness, bias of microwave beam over the Earth's surface due to the refraction in the ionosphere, magnetic rotation of the electromagnetic wave in a magnetic field and the nonlinear interaction between radiation and ionosphere.

If on the frequency of 2.5 - 3 GHz, the microwave energy absorption is equal to 0.05 db, this absorption increasing sharply with the frequency increase up to frequency equal to 30 GHz. However, in the frequency range of 35 - 38 GHz, corresponding to the millimetre waves, there exists in the Earth's atmosphere so-called "radiowindow" in which sharp absorption decrease up to 0.4 db is observed. From the analysis of all listed phenomena, accompanying the process of energy transfer using a beam, it follows that - besides the absorption - the main contribution to the microwave energy decay makes the electromagnetic wave dispersion when cloudiness, rain or mist are present. The contribution of other processes is essentially smaller. Taking into account the fact that the Earth's surface is closed by cloudiness during approximately 20% of the time, and during approximately 6% of the time, the precipitation of different intensity is observed, the corresponding losses of microwave energy at the frequency 2.5 - 3 GHz are estimated as being 2% - 6%.

An analogous analysis, carried out for the microwave radiation in the frequency range of 35-38 GHz, has shown that the losses in the mist amount to 0.01 db and under conditions of a dense mist and slight rains the corresponding losses equals to 0.8 db. It is necessary to note that greater decay up to 12 db can appear in dense cumulus-rain clouds and heavy rain, the share of which in the time of precipitation equals only 2% in the Earth middle latitudes. Taking into account that the annual fall of precipitation averages 0.1% of the time, the conclusion can be drawn concerning the possibility of energy transmission through the Earth's atmosphere by means of a microwave beam on the frequencies in the range of 35 - 38 GHz. Besides, there exists a number of measures for the decrease of negative influence of rains and cloudiness upon the passage of microwave beam. These measures include: placing the receiving ground antenna in the regions with small quantity of overcast and rainy days, using several reserve antennas in different regions with sufficient distance between them, taking account of the local character of rains and cloudiness, and also - the realization of possibility of active action on rain clouds in order to provoke the precipitation. Thus, the losses of microwave energy during the power transmission by means of a beam on the frequency in the range of 35 - 38 GHz can be estimated as equal to 8% - 11%. This is only 1.5 - 2 times worse than the analogous parameter when using the radiation with frequency equal to 2.5 - 3 GHz. Taking into account the fact that energy losses, connected with energy transportation by means of a beam, make up an insignificant part of the total energy losses in projects considered, it can be said that worsening the energy transfer process when passing to the wave millimeter range is quite acceptable. The point is that under conditions of maintaining the values of A_2, L and τ, more than 100-fold decrease of the orbital transmitting antenna area A_t is possible. It is obvious that a similar measure must considerably decrease the mass and overall dimensions of an orbital power station.

The factor which hamper the practical use of proposed frequency range (35 - 38 GHZ) include the limited choice of powerful and highly efficient microwave radiation sources in this range. However the appearance of such schemes of microwave energy converters as gyrotrons, masers and lasers on the free electrons will permit to hope for overcoming

these difficulties in the near future.

The use of other existing "radiowindows" in the Earth's atmosphere and, in particular, more short-wave "radiowindows" on the "transparency" frequency in the range of 140 GHZ and 220 GHz represents a more remote perspective.

SPS 91

B8.3 The way of VHF power transmission from the solar energy space installation by generating video impulses

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ABSTRACT

In report the possibility of SHF-power transmission from the space power station by means of videoimpulse generation is considered. In addition to analysys of element base technical characteristics , that provides the pos..ibility of considered method implementation , the adventages of one are discussed in comparing with tradi- tional continnous generation regime. The main characteristics of the experimental impulse SHF-generator are adduced and the dir..ctions of their improvement are shown

RESUME

Ce rapport examine la possibilité de transmission d'énergie depuis le satellite d'une centrale solaire spatiale par impulsions vidéo. Les caractéristiques du système sont présentées, ainsi que ses avantages, par rapport au régime continu de transmission d'énergie. Les principales caractéristiques d'un générateur expérimental sont présentées ainsi que les évolutions envisageables de ce système.

INTRODUCTION

The system of VHF-power generation is one of determinative parts of space solar power plant. However it is need to consider that system constr..ction in complex with radiation system. The effective power transmission from solar space power plant (SSPP),having tens and hundreds megawatts profitable power, may be fulfiled only with using of phased active arrays (PAA). Here must be observed two conditions : directional diagram (DD) must be sufficiently narrow with minimal radiate power in lateral lobes and SHF - power frequ..ncy must be in the "transparency window" of the earth atmosphere. The first "transparency window" may be limited by 100 MHz from bellow (at frequ..ncy higher than 100 MHz it ispossible to disgard the absorbtion in the ionosphere) and by 10 GHz from above, as at more higher frequencies the SHF-power attenuation is abruptly grow due to molecular absorbtion. So the sufficiently wide spectrum of permissible frequencies allow to use different element basefor SHF-power generation.It is more difficult to meet requirement, restricting the form of DD - the absence of lateral lobes, that pecular for radiation of antenna with excitation by monochromatic signals.

Let us consider possibility of that problem resolving with the help of excitation of radiator,for example of the restricted length depole,by short video impulse.

CONCEPT SURVEY

First of all,let us estimate DD of such antena.In the conditions when the excite impulse space extension CΔT (C-speed of light,ΔT-impulse duration) essentially lesser then dipole dimensions,the field in the observation pointis the superposition of fields,emitted by separate portions of antenna.The possibility of partial field investigation and of separate emittings separate centres isolationis arise here.

Let linear antenna of lenght L consist. from array of Herz depoles, being excited simultaneously by short video impulse (Fig.1).Then at point

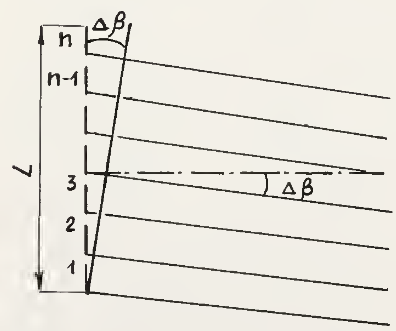

Fig.1

of far zone, that lied on the normal to disclosure, the impulse fields from elementary depoles will arise simultaneously and therefore the field of the whole antenna will be equall to sum of elementary fields (in accordance with far one definition). For the direction , that has angle β referenceto normal , the moment of field impulse origin from extreme

an tena element will be shifted on the value Δt in respect to moment of field impulse origin from element, placed on contrary antena border and besides

$$\Delta t = (L \sin \beta)/C \qquad (1)$$

While $\Delta t < \Delta T$ the maximum of sum field in a far zone will not be change.
But as β receive such value ,that will be $\Delta t \geqslant \Delta T$, so the sum field in the far zone will be decrease.With large number antena elements the field reduction on 3 db at far zone will occur when the following condition take place

$$((L / \sqrt{2}) \sin\beta_k)/C = \Delta T \qquad (2)$$

The value $\beta = \beta_k$ may be considered as the diagram half-width ($\beta=\theta/2$).Then,taken in account ,that $\sin \beta_k \approx \beta_k = \theta/2$, we reseave

$$\theta = 2\sqrt{2}\ C\ \Delta T/L \qquad (3)$$

Using (3) , it is easy to estimate the antenna amplification factor G for nonsinusoidal waves. The main part of the power the antena radiates at a plane angle θ or (for round plane radiator) at a space angle θ^2, therefore

$$G = 4\pi/\theta^2 = \pi L^2/(2C^2 \Delta T^2) \qquad (4)$$

In connect with consedered and at condition of large periodicity of impulses , radiated by antenna , that is at

$$T \gg \Delta t > \Delta T , \qquad (5)$$

where T - period of impulses follow , it is possible to confirm ,that the coincidence probability of impulse from many radiators for directions,essentially derivative from normal , is small. It signify, that at such manner of antena excitation in its DD the lateral lobes will be absent.

Without community restriction that chematical consideration of DD forming question may be used for estimation of active phased array DD.

Let us consider methods of generation of powerful video impulses for supply of emitting elements of PAA with new elemenet base using - drift diode with abrupt restore (DDAR) and avalanche sharpening diode (ASD)[1]. DDAR is able to form impulse of nanosecond duration ($\Delta f=1/\Delta t=300$ MHz), ASD- of subnanosecond duration ($\Delta f=1/\Delta t=2$ GHz), that is the main impulse frequencies, that formed with above elements using, are inside of "transparency window". The choice of the impulse duration and, consequently, of the forming element need to consider in connection with PAA construction, that means the optimization problem and deviate from the framework of our work, that has an conceptual character.

Let us consider module with DDAR. DDAR is essentially an current breaker, that give ability for module construction by means of scheme with intermediate energy accumulation in inductive accumulator,where the output impulse is formed with sharp current breaking in circuit, consisting of sequentialy connected DDAR and inductance. At Fig.2 the two-stroke module sheme is shown.

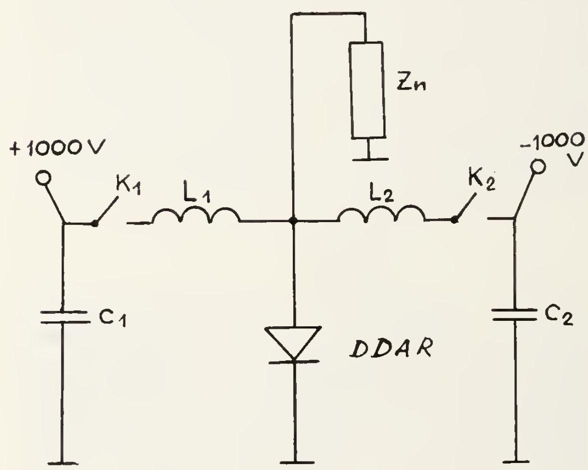

Fig.2

The scheme work in following manner. At contour L_1C_1 key K_1 closure in a duration of first oscillation half-period the pumping current I_1 is flow through DDAR. At moment of current I_1 direction change by means of key K_2 closure the contour of reflux L_2C_2, identical to, contour L_1C_1 is switch on.The current I_2 of that contour is summarized with current I_1 in DDAR. At correct choice of DDAR and of contour parameters correlation the follow conditions must be observed: firstly , at moment of summarized current maximum the charge , that take out from DDAR , is equal to introduced one (with accuracy of loss at keys and DDAR), then current through DDAR is breaking and summarized contour current ($I_1 + I_2$) is transfered at load (radiator); secondly, current form must to have maximum time derivative at $i = (I_1 + I_2)/2$, that allow to construct on the load the bellshaped form impulse without derivative jump ; thirdly,the relation $2\pi\tau L^* \gg Z_n$ (where Z_n - load impedance, τ- duration of transient process of current breaking through DDAR , L^* - equivalent inductance of both contours, must be fulfiled, that allow to transfer all current at load. With DDAR help it is possible to form the impulse of crest power 1-3 MW. The impulse frequency is defined by keys frequency properties and approximatly equal 40-50 KHz for thyristor (with small life time of nonprimary charge carriers). Thus, the average power of one module 9 with impulse half-width 5 nc) approximatly equal 700 W. Note, that the unstability of above module start is less then 100 nc, that allow to fulfil corresponding sinhronization both for parallel work of some modules on the ane emitting element PAA , and for feeding of emitting elements of all PAA. The dignity of module on the DDAR is that it

is necessary relativly small (1000 V) direct voltage from solar batterys (see Fig.2).With help of module on the ASD it is possible to form impulse with half-width 0.2-0.3 nc and peak power until 500 KW. The ASD is an element of sharpening type and can to work in connection with module on the DDAR, moreover one module on DDAR can to start until 100 modules on the ASD. The average power , formed by one module on the ASD, is equal 5 W , however the ASD dimensions are compose 0,1cm... and the high stability of the ASD start (the unstability is less 20 pc) allow its parallel connection.

Thus, with help of considered modules it is possible to carry out,in our opinion, the perspective excitation method of emitting part of SSPP.

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B8.4 Space power supply network using laser beams

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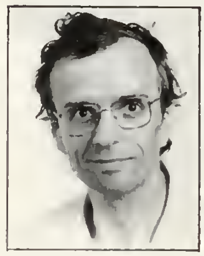

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Abstract :

This paper describes laser-based space power supply networks which could perhaps be feasible within several decades. These networks could be used to supply energy satellites in low earth orbit (LEO) or geostationary earth orbit (GEO), either to meet extra energy requirements or to allow a shift in orbit. In addition, they could be used to transmit energy towards the Earth or lunar bases, as well as many other space power applications. Also described are the different types of lasers which could be used in such networks, and the advantages of these networks in terms of satellite design.

Résumé :

On décrit ici l'architecture de réseaux spatiaux d'alimentation en puissance utilisant des faisceaux laser qui pourraient peut-être être construits dans quelques décades. On pourrait alors envisager l'alimentation en énergie de satellites en orbite basse ou géostationnaire pour leurs besoins internes excédentaires ou pour changer d'orbite et aussi des transmissions d'énergie vers la terre ou vers des bases lunaires ou pour toute autre application spatiale. On décrit les types de lasers qui pourraient être utilisés dans de tels réseaux et les avantages que procureraient ceux-ci pour la conception des satellites.

1. Introduction

Following are four examples of laser-based space power supply networks that could perhaps be feasible within several decades.

2. Future power needs in space

The concept of a space power supply using laser beams appears very promising to supply energy to satellites, for their excess internal needs or to maintain their orbit or to change it, as well as to supply power to lunar bases, to transmit energy from space to Earth or for many other space applications. A study by EUROSPACE [1] indicates that space energy needs will show considerable growth after 1995.

3. Description of different networks

3.1. Low orbit laser supply network without relay mirrors

Figure 1 describes a low orbit laser supply network without relay mirrors designed mainly to supply low earth orbit (LEO) or geostationary earth orbit (GEO) satellites or lunar bases from lasers in LEO. The LEO laser satellite comprises large solar panels or light concentrators. It must be located at an average altitude of about 1000 km in order to avoid the residual atmospheric braking effect and therefore provide the required long life span.

3.2. Low orbit laser supply network with relay mirrors

In the previous network each laser acts independently. To improve system efficiency and redundancy, and to avoid sun eclipses, relay mirrors can be used as shown in Figure 2, the different lasers being interconnected. In this case the power generated from several lasers is directed successively towards several relay mirror satellites. These relay mirrors select a part of the beam and direct it via pointing optics towards all space object which need power. It is worth noting that for LEO receivers the dimensions of the laser beam receiving panels are smaller than equivalent solar

panels. Indeed not only can the irradiance of a focused laser beam be much greater that the one given by solar irradiance but the power conversion effiency is greater when appropriate monochromatic laser wavelengths are used. We can therefore predict that the braking effect related to the LEO receiving satellite is generally smaller than that for conventional satellites. In addition the receiving panels' weight is reduced.

3.3. Geostationary orbit laser supply network with relay mirrors

The third system shown in Figure 3 is a geostationary orbit laser supply network with relay mirrors mainly supplying GEO satellites. Direct GEO-Earth transmission can also be considered in this case. This network can be coupled to an LEO network.

3.4. Geostationary supply network with ground-based laser

The fourth system is a geostationary supply network using ground-based lasers. To cope with local weather conditions which interfere with ground to space transmissions, several lasers must be used, each at a different location and with unrelated weather (for example, on different continents).

The diagram in Fig. 5 shows an example of this system, including relay mirrors, laser and pointing optics.

4. Optics and pointing requirements

Good laser transmission efficiency assumes that the diameter DE of the emission optics is approximated by the formula: $DE = 2{,}44\ \lambda \times Z\ /\ DR$, with DR the receiver diameter, λ the wavelength and Z the distance between emitter and receiver (Fig. 6). For the following calculations λ has been set at 0.8 µm. For example, in the case of Fig. 1, with Z=7,500 km and DR=3 m, DE is equal to 4.9 m.

In the case of Fig. 2, the diameter of the relay mirror is about 4 m, and the other parameters remain the same. In the case of Fig. 3 with Z=40,000 km, the relay mirror diameter is about 9 m (in this case DE=DR).

For an LEO satellite supplying energy to a lunar base, the diameter of the optics on the satellite would be 10 m, and the diameter of the energy collector on the moon's surface would be 75 m. This would provide a convenient and permanent power supply for a lunar base, even at "night". Pointing accuracy (at 3 r.m.s) on the order of $\lambda/DE/2$ is required. For DE=10 m and λ=0.8 mm, $\lambda/DE/2$=40 nanoradians. By using adaptive optics, such accuracy appears feasible in the near future. The same conclusion applies to the large relay mirrors, based on the used of segmented phased mirror technology [2]. Ref. 3 provides further details about these aspects.

5. Laser systems in space

Today, based on efficiency, technology and power criteria, four types of lasers can be considered for use in these networks:

- laser diode-pumped solid-state lasers,
- phased arrays of semiconductor lasers,
- solid-state sun-pumped lasers,
- free electron lasers (FEL).

This order also corresponds to the most likely timetable for using these lasers in space applications. In the very short term, laser diode-pumped solid-state lasers are the only lasers that can emit a near diffraction limited beam, to an average power of about one kilowatt, (although with weak overall efficiency). Moreover, the emission wavelength (about 1 µm) requires the use of photovoltaic cells specially designed to obtain good conversion efficiency (compound cells).

The state of the art in the domain of high power semiconductor lasers arrays is not still sufficiently advanced to enable energy transmission at short term. Indeed, these arrays must be phase-matched in order to obtain a beam in fundamental space mode. Today, many laboratories are working on these questions; the best reported performance to date is 16 W in pulsed mode [4].

If the phased-array laser diode technology succeeds in the near future, and if significant power levels are obtained on the fundamental mode, this type of laser would replace laser diode-pumped solid state media. Total efficiency could be multiplied by six or more and the system complexity would be reduced in consequence.

With directly sun-pumped lasers, the conversion efficiency must be greater since there is a direct photon-photon conversion process. This laser technology should therefore take on more importance in space applications. Nevertheless, the efficiency obtained with these lasers today is rather weak, due to the fact that absorption spectra of studied amplifier media are not well matched to solar spectrum: sharp lines or badly centered compared with this spectrum. For example, the use factor of sun energy is only 3% for iodine laser ($t\text{-}C_4F_9I$ gas) at 1.3 µm. With solid state materials like Nd:YAG, the very numerous absorption lines distributed in the visible spectrum would give good overall efficiency; the absorption efficiency for a 5900 K black body reaches 11% with Nd:YAG and 26% with codoped Nd:Cr:GSGG matrix [5]. The experiments carried out with Nd:YAG have given promising results (1.5% overall efficiency, emitted power > 60 W) but this is still insufficient, due to the thermal effect of the pumping process and the accuracy of sun-pumped laser medium coupling.

Today the sun-pumped laser appears very promising, in particular due to the availability of a new type of solid-state laser medium. For example, the Alexandrite or $Ti:Al_2O_3$ crystals have an absorption band well centered on the sun spectrum, a high quantum efficiency and a thermal conductivity better than most other materials.

Within this context solid state sun-pumped lasers promise higher efficiency. Note that the use of a $Ti:Al_2O_3$ crystal might be questionable because such sources require high concentration collector. Finally even though little work has been done on sun pumped lasers, their development for power transmission in space seems very promising. Compared to other candidates, their advantages include:

- the photon-photon conversion process, which allows the use of reflectors which are lighter and smaller than solar panels;
- a direct conversion which eliminates additional energy consumption through intermediate processes;
-overall efficiency fairly competitive with other laser candidates (sun-laser efficiency ratio: 5 to 10%);
- a less complex and more rugged technology;
- an emission band (0.7 -1 µm) well matched to the quantum efficiency curve of Si or GaAs cells.

In conclusion, sun-pumped laser research and development phases should focus on the following points:

- optimization of the conversion efficiency of sunlight to laser light;
- thermal issues:
- geometrical amplifier design able to increase conversion efficiency and lessen thermal effects;
    - effective heat removal;
    - elimination of useless solar flux;
    - research to find the best crystal.

The following table shows the global efficiency ρ of different kinds of laser systems assuming a 20% solar cell efficiency (except for sun-pumped lasers which don't use these cells).

	ρ	λ
Diode laser pumped solid laser	1 to 2%	1.06 µm
Laser diode arrays	6%	0.8 µm
Sun pumped solid state laser	5 to 10%	0.7 to 1 µm
Free electron laser	max. 6%	tunable

A more complete analysis would take into account collector or solar cells and radiator masses.

The paper "problèmes posés par la transmission d'énergie par faisceaux laser" given by M.Gaillard and A.Laurens at the last SPS symposium, discussed different types of lasers, including FEL. At that time, FEL performance was being studied, and progress in this field would change many concepts in microwave and optics. Since then, FELs have indeed advanced and could be good candidates for energy transmission from Earth to satellites and, possibly in the distant future, for big orbital stations.

The main advantages of FELs are:
-tunability of the wavelength;
-high laser beam quality;
-high efficiency.

Wavelength tunability is very advantageous for propagation through the atmosphere and photovoltaic cell conversion efficiency. There are good transmission windows around 1 and 2 micrometers. The advantage of a wavelength of about 1 micrometer is associating high transmission capacity with relatively small optics. Shorter wavelength FELs, however have decreased efficiency and require higher qualities of the electron beam.

For high energy, there were two candidates at the time of this paper:
- induction LINAC,
- radio-frequency LINAC.

Last years electron beam qualities were poor (normalized emittance ε_N defined as $\gamma\pi\rho\theta$ where ρ is the radius, θ the half-angle at any beam focus and γ the relativist factor; and energy dispersion) compared to the requirements of short wavelengths.

Since then, induction LINAC have been left for this wavelength field, because it seemed very difficult to obtain the required electron beam qualities.

On the other hand, new technologies, using photoinjectors (Los Alamos) or grid modulated electrostatic electron gun (TRW), minimizes space charge effect and thus allow low emittances.

For example, the photocathode at the High Brightness Accelerator Facility (HIBAF, at Los Alamos National Laboratory) is in the wall of the first RF cavity; owing to the very high electric field (26 MV/m), electrons become very quickly relativistic: space charge effects become negligible. Table 1 indicates emittances and energy dispersions of some FELs, given at the 12th FEL International Conference held in PARIS from Sept. 17 to 21, 1990

Table 1

	$\Delta E/E$	ε_N	micropulse charge
HIBAF [7] (LANL)	0.3%	$30\ \pi$ µm mrad $50\ \pi$ µm mrad	1 nC 9 nC
GBFEL [8] Ground Based Free Electron Laser for White Sands Missile Range		$25\ \pi$ µm mrad (calculated)	8 nC
TRW [6, 9]		$8\ \pi$ µm mrad	1 nC

This is a major improvement, since characteristics of RF Linacs were about $\varepsilon_N = 150\ \pi$ mm mrad and $\Delta E/E = 1\%$.

RF linacs with superconductivity cavities (TRW) should give better performance:
- $\Delta E/E = 0.1\%$ thanks to high electric field stability;
- lower emittance, thanks to a higher electric field and a better absorption of High Order Modes (HOM).

Moreover, RF Linacs with superconducting cavities

have major advantages for our applications:
- low Ohm losses on the cavity walls permitting continuous working: average laser powers of several megawatts appear possible.
- high electric fields (10 MV/m) allowing compact LINACs (an electron energy of 100 MeV is necessary to obtain 1 μm wavelength), which is essential for space use.
- possibility of recovering the unspent energy of the electrons after the wiggler exit by recirculating the beam through the same RF superconducting cavities, converting it back to RF energy. By recovering unspent energy, overall efficiency including klystron efficiency could reach 30% or more (see Fig. 7).

It is very important to note that superconducting cavities technology is well known and the fabrication process is reliable. Moreover CERN makes cavities in Niobium-Titanium, with a higher critical temperature.

In conclusion, RF LINACs with superconducting cavities seem to be a good concept for future FELs with average power of several megawatts and overall efficiency of 30% or more. For lower average power, compact FELs are a possibility. For example, racetrack microtrons is a path to be explored.

6. Conclusion

Due to its short wavelength, laser transmission of energy in space can be envisaged over distances of many thousands of kilometers. We hope that within several decades, lasers, optics and pointing systems will be technologically advanced enough to meet space requirements. We think that such networks offer many advantages on the satellite design level. The study and development of such projects however, would require international agreement and cooperation.

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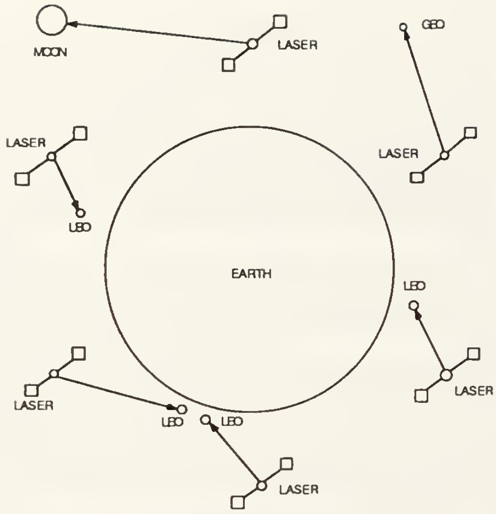


FIG. 1 LOW ORBIT LASER SUPPLY NETWORK WITHOUT RELAY MIRRORS

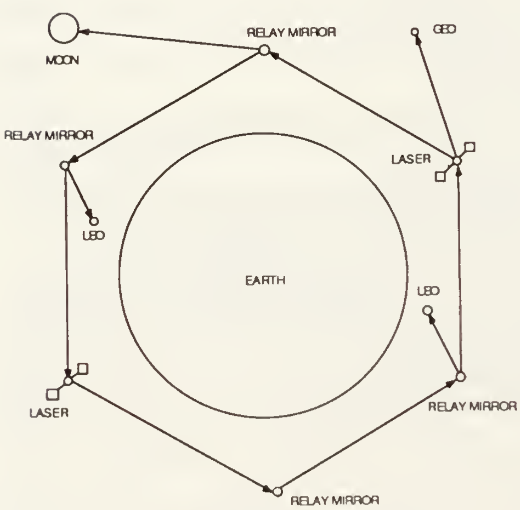


FIG. 2 LOW ORBIT LASER SUPPLY NETWORK WITH RELAY MIRRORS

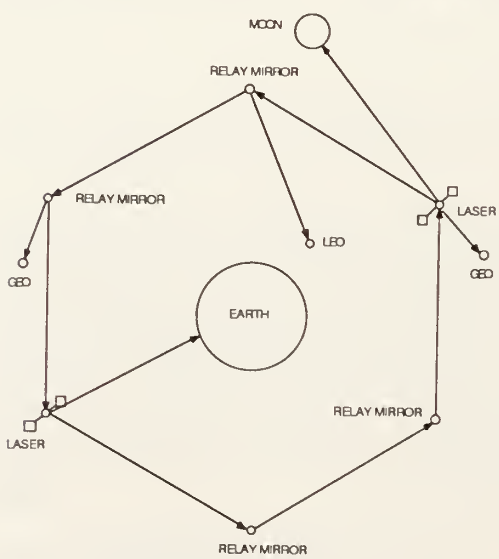


FIG. 3 GEOSTATIONARY ORBIT LASER SUPPLY NETWORK WITH RELAY MIRRORS.

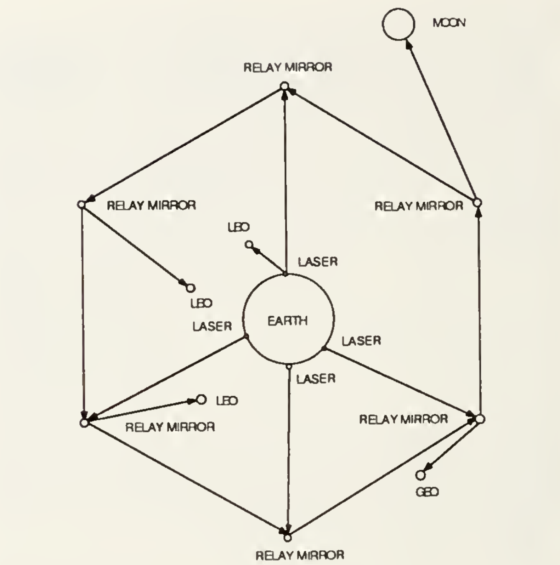


FIG. 4 GEOSTATIONARY SUPPLY NETWORK WITH GROUND-BASED LASER

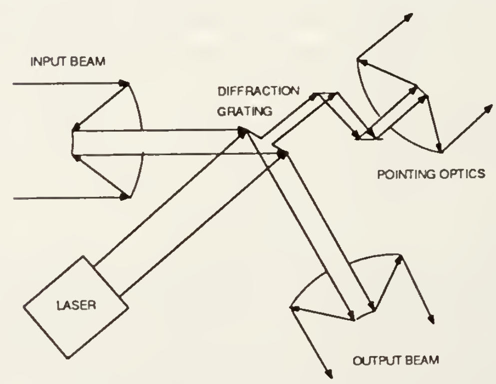


FIG. 5 RELAY MIRRORS, LASER AND POINTING OPTICS

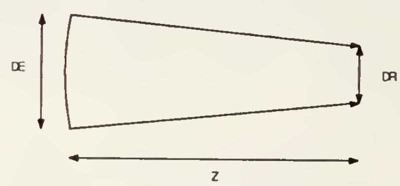
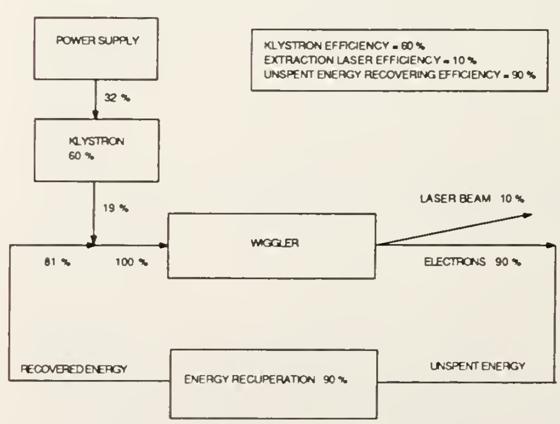


FIG. 6 LASER BEAM GEOMETRY



$$\text{OVERALL EFFICIENCY} = \frac{\text{LASER ENERGY}}{\text{POWER SUPPLY ENERGY}} = 0\ 31$$

FIG 7 EFFICIENCY WITH ENERGY RECOVERING

B8.5 High precision laser pointing experiment for power transmission

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High precision laser pointing is one of the required key technologies for space to space and space to Earth power transmission, respectively. The related technologies have to be verified by a realistic space experiment taking into account both accuracy and safety aspects of high energy laser beam pointing. Typical underlying technologies of such an experiment will be reviewed w.r.t. to pointing technologies developed by MBB for the 1 m Planetary Telescope, which has to achieve 0.01 arcsec pointing accuracy via on-board image processing, and w.r.t. the 60 m optical delay line of ESO's Very Large Telescope Interferometer, where an optical path length stability < 9 nm at 100 Hz has to be achieved. Simulation results for an image processing stabilized laser system will be presented.

C1.1 The SPS economic and ecological consequences

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Some consequences of the SPS engineering, excepting dramatic destruction due to the faults of the energy beam steering system, are considered. Even the normal function of the cosmic-Earth microwave energy bridge is at the bottom of serious problems.

The Earth's stationary orbits of SPS and every possible location of Earth's energy receiving points will cause a wide spectrum of necessary space-orientated energy beams, that "perforate" the near-Earth space and atmosphere. There are, evidently, some rigid restrictions in the choice of possible location of Earth station due to the obligatory prevention of possible intersections of microwave energy beams with space orbit satellite and aviation traffic, season and random bird and insect emigration traces, that must be included in the total cost of the SPS engineering.

The SPS engineering can cause a wide variety of anomalous phenomena in the Earth atmosphere due to powerful non-linear perturbation effects of "atmosphere-perforated" energy beams :

1)irreversible changing of air flow and atmosphere electricity processes (microwave energy beam is a more powerful factor than the known "Lorentz butterfly" in the theory of dynamic chaos),

2)obstacles to wireless communication links, etc.

There is a need for careful investigation programs of the global consequences of SPS engineering before its wide application, using the methods of the theory of dynamic systems, synergetics, etc.

C1.2 Six port junctions for the control of phased array antennas on Microwave power satellites

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SUMMARY

This paper shows that six-port techniques can be advantageously used for the control of phased array antennas on microwave power satellites. The relative amplitude and phase of each microwave signal generated by one radiator can be measured by inserting a six-port junction between the radiator and the generator and by coding the signal using low frequency amplitude modulation (kHz).

RÉSUMÉ

Cet article montre que la technique de mesure six-port pourrait être utilisée pour l'asservissement des réseaux d'antennes dans les centrales solaires orbitales. La phase et l'amplitude relative de chaque signal généré par un radiateur pourraient être mesurées en insérant une jonction six-port entre le générateur et l'antenne radiateur et en codant chaque signal émanant de chaque générateur par une modulation d'amplitude à faible fréquence (kHz).

Introduction

The use of microwave energy in space power transmission systems has already been proposed in a number of projects [1, 2]. In most cases, high power microwave beams are generated from a large number of microwave radiators placed in a phased array antenna configuration. The microwave energy is then converted, at the receiving end into DC energy with a rectenna array [3]. The direction of the generated microwave beam is dependent on the control of the individual phases and amplitudes of the signals at each radiating element [4]. For space power satellites it is best to operate the power generators in non-linear regions to obtain maximum efficiency in power conversion and also to obtain the maximum possible ratio of microwave power to generator weight.

In a large signal operating mode, the phase of the generated microwave signal is very sensitive to variations in the operating parameters (RF power level, DC voltages, load impedances, etc.). It is therefore desireable to measure and then control, as required, the phases and the amplitudes of all the microwave signals reaching the radiating elements in the antenna array.

This paper examines the use of six-port junctions to make such measurements. Linear six-port circuits have been widely used [5] at low power levels and in some cases at relatively high power levels (1 KW at 2450 MHz) [6]. In order to generate a 1 GW beam of microwave power it would be necessary to operate a 1000 x 1000 element array of 1 KW radiators. The advantages of using 1 KW generators, similar to microwave oven magnetrons (700 W), have already been given in the literature [3]. Such generators are presently mass produced for the microwave oven market at a very low cost; the frequency of operation is also about correct to minimize diffraction effects in the ionosphere, etc.

Six-port junctions

The use of six-port junctions for the measurement of reflection coefficients, S- parameters, impedances, power flow, etc., has been in use for many years [5, 6, 7]. More recently, a six-port junction was used to measure the relative amplitude and phase of two oppositely directed waves on a transmission line where the reflected wave was launched by a signal generator rather than by an impedance mismatch. This principle has been used for automated multi-harmonic load-pull measurements [8]. The same principle has been also used for antenna polarization measurements [9].

A six-port junction is illustrated in fig.1. The six-port is generally made by using a number of microwave components (power dividers, hybrids, etc.) connected together such that the three Q points [5] are defined and well separated at each operating frequency. Once the six-port junction is calibrated (the position of the Q points in the complex plane are known), it is possible to determine the reflection coefficient by measuring the relative power levels at each of the four output ports [10].

Calibration and Interface

The calibration procedure to determine the position of the Q points is very important and many methods have been tried out. Different methodologies were used to relate the four power readings to the complex reflection coefficient including linear and non linear formulation [10, 11, 12]. The number of standard loads as well as the computational effort to calibrate the six-port reflectometer are the most important criteria in the selection of any appropriate calibration method. One of the most convenient was proposed in reference [10].

For the purpose of controlling a large number of channels, it is best to convert the RF power readings from each junction into a digital format for control and measurement by a central computer via a bus (e.g. IEEE-488) using optical fiber transmission lines. Such an arrangement can facilitate the gathering of the numerous readings at a central computer for numerical processing and beam control purposes.

Configuration for an "N" channel array

Figure 2 shows a block diagram of an N channel array where each channel contains a microwave power generator, a module for amplitude and phase control, a six-port junction and a radiating element. The microwave signals at each radiator are necessarily at the same frequency and the only variables are signal phases and amplitudes.

The "pseudo-reflection coefficients" measured in each channel by the six-port correspond to the ratios of a number of reflected waves to the incident wave generated by the reference channel generator. The reflected waves can originate from: the actual physical reflections within the transmission line itself (Γ_0); and various signals generated by mutual coupling between a radiating element and its nearest neighbours. Thus, in a reference channel "0" can be measured four reflection coefficients Γ_{0E}, Γ_{0W}, Γ_{0S} , Γ_{0N} which correspond to the reflection coefficients of the various waves coupled into the reference channel (0) from the nearest radiators (E, W, N, S). In addition, a reflection coefficient Γ_{00} corresponding to the reference channel mismatch can also be obtained. In all cases, the six-port junction can provide all the above required reflection coefficients if the signals are coded, e.g. by a low frequency amplitude modulation [12]. Thus, a change in the reflection coefficient Γ_{0E} corresponds to a change in phase between the reference channel (0) and the adjacent eastern channel (E). When all the channels of the array contain a six-port, it is then possible to measure and control the relative phase differences between channel (0) and a given E, W, N, S channel. An appropriate signal code pattern for the array can be used for channel identification such that the various reflection coefficients between channel (0) and adjacent channels can be identified from the measurements (Fig.3).

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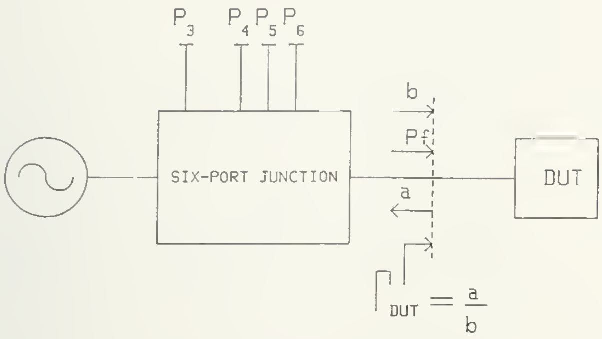

Figure 1

Six-port reflectometer

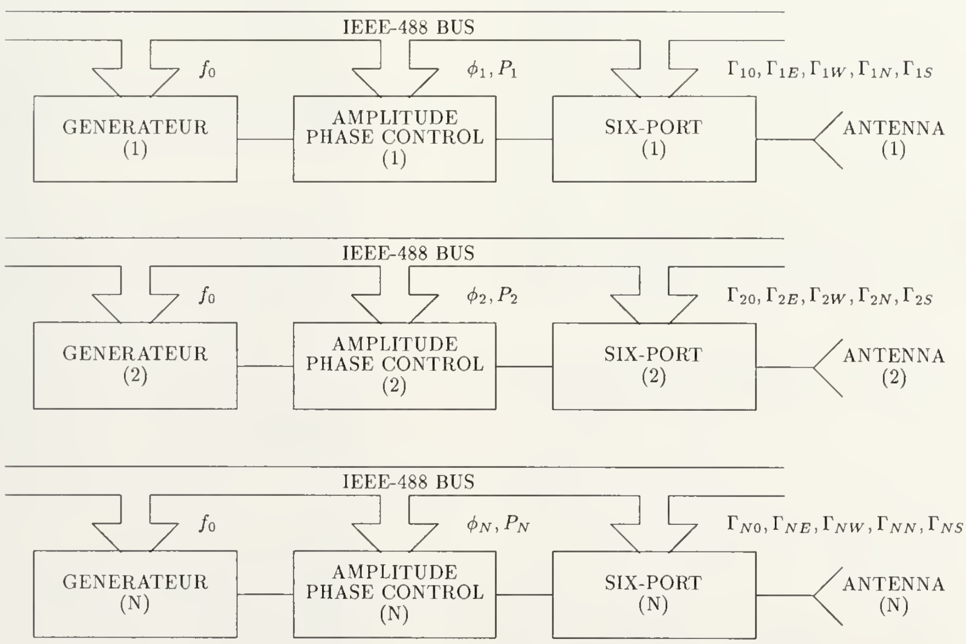

Figure 2

Block diagram of microwave power antenna channels fitted with six-port junctions

A	B	C	A	B	C
F	E	D	F	E	D
G	H	I	G	H	I
A	B	C	A	B	C
F	E	D	F	E	D
G	H	I	G	H	I

Figure 3

Channel codes to enable the measurement of phase and amplitude between any reference channels and nearest neighborring channels of the array antennas

SPS 91

C1.3 Space nuclear power system studies in France

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Abstract

A cooperative program (ERATO Project) between CNES and CEA was initiated in 1982 to investigate the feasibility, development, cost, and lead time of 20 to 200 kWe space nuclear power system adapted to powering different space missions as space based radar for earth observation (20 kWe), LEO-GEO orbit transfer vehicle (OTV) and space transportation systems using electrical propulsion (200 to 400 kWe).

Several concepts of nuclear power systems have been studied as :

- a 200 kWe power system operating at very high temperature and needing a long development program,

- a 20 kWe power system using available technologies developped for terrestrial nuclear reactors achievable in 10-12 years.

Résumé

Un programme coopératif (projet ERATO) entre le CNES et le CEA a été lancé en 1982 pour étudier la faisabilité, le coût et le délai de développement de générateurs électronucléaires spatiaux pour l'alimentation de différentes missions spatiales : radar d'observation de la terre (20 kWe), remorqueur interorbital LEO-GEO et système de propulsion électrique (200 à 400 kWe).

Plusieurs concept de générateurs ont été étudiés, en particulier :

- un générateur de 200 kWe fonctionnant à très haute température nécessitant un long programme de développement,

- un générateur de 20 kWe utilisant largement des technologies existantes developpées pour les réacteurs nucléaires terrestres.

I - Introduction

The load carrying capability of the Ariane V heavy launcher (12 T. at 800 km, altitude), which will be available after years 1995, opens up the prospects of futur European space missions with projected energy needs and lifetime relevant to nuclear power systems.

In order to assess the engineering feasibility, the lead time and the development cost of such nuclear power systems, a cooperative study program, the ERATO project, was initiated in 1982 between the Centre National d'Etudes Spatiale (CNES) and the Commissariat à l'Energie Atomique (CEA).

The first study phase (1983 to mid 1986) consisted in conceptual studies, operating transient analyses and cost assessment of a reference 200 kwe nuclear Brayton system, meeting the power needs of an orbit transfer vehicle with electric propulsion. This effort has been pursued in the form of a second 3 year study phase (mid 1986 to mid 1989), with the objective of assessing the technical and economical bases for the development of a 20 kwe nuclear power system, likely to meet the energy needs of European space missions from year 2005 onwards. With this aim in view, a comprehensive study program of 20 kwe nuclear power systems has been conducted to provide the basis for selecting the design options and the development strategy of a first European space nuclear system.

II - Reference missions for ERATO project

The first phase of the ERATO project has been devoted to a reference 200 kwe nuclear power system, compatible with the Ariane V launcher, furnishing the electric propulsion system of an orbit transfer vehicle (OTV) for high mass payload transfer from low earth orbit (Ariane launcher delivery orbit) to higher orbit (GEO for instance). There are three basic types of electric propulsion.

- electrothermal devices, in which electrical energy is used to heat a propellant gas which is then expanded in a nozzle.

- electrostatic devices in which electrical energy is used to ionise a

propellant gas and accelerate the ions at high velocity.

- electrotromagnetic devices in which electrical energy is used to create a neutral plasma propellant gas and expel it at high velocity.

The specific impulse of electric propulsion is typically 3000 S compared with 300 S of chemical propulsion. Electric propulsion therefore offers subsantial propellant mass savings.

But with electric propulsion the electric power to thrust ratio is high, typically 25 kw/N, and to limit the duration of the transfer of a high mass payload from LEO to GEO high electric power for long operating time is required. Using a 200 kwe generator, the ERATO reference power, and a mercury or xenon ion engine, the transfer duration for a 8 T payload from a 800 km altitude orbit to GEO is 75 days, and 30 days for the return trip from GEO to LEO.

Only nuclear power generators present the good characteristics for high mass payload electric propulsion : high electric power, long operating duration and long operating lifetime.

The development of high electric power nuclear sources will make electric propulsion a powerful contender for very large spacecraft and high energy missions : solar system and outer planet exploration. The first one could be a Mars mission.

In the second phase of the ERATO project we have investigated a 20 kwe space nuclear power system adapted to a space based radar for earth observation. Main mission and spacecraft specifications were :

- near polar orbit at approximately 1000 km altitude,

- radar available at all times on all portion of the orbit,

- electric source power (radar power, signal processing, mission module) : 20 kwe,

- total mass for the electric power system : below 2,5 T.

Of course uses of 20 and 200 kwe nuclear power sources are not limited to electric propulsion and space based radar. Many missions will become possible when 20-200 kwe power sources will be available : GEO communications platform, Air-Ocean traffic control, advanced space transportation systems for SPS construction, planetary exploration, Lunar or Mars base supply...

For the time we have not envisaged manned missions because they need a high mass protection shield which highly increases the nuclear generator mass and requires several launchings and on orbit assembly.

III - Safety Aspects of nuclear power systems in space

Launch and operation of a nuclear reactor in space rise a number of specific safety problems which can be managed with an appropriate design of the reactor and the observance of specific operating rules during launch, in orbit and after the final reactor shut down at end of life.

Main potential accidents to consider during prelaunch and lauch phases are : explosion, fire, ground impact, sea immersion, reentry in high altitude atmosphere. During power operation in orbit loss of coolant and over power accidents may occur. At end of life, in case of atmospheric reentry radioactive materials dispersion in atmosphere may happen.

In all cases the primary objective is to minimize the protential radiation exposure of population and the release of radioactive materials in space and terrestrial environment.

In order to avoid any contamination with Plutonium 239, only fully enriched uranium will be used.

The reactor will be launched as an inactive unit and maintained largely subcritical until its first start up in orbit. So on the ground and through the lauch phases no hazardous radioactive materials (fission products) will be present in the reactor core. The unburned nuclear fuel presents a negligible hazard.

To prevent criticallity accident in case of compaction of the reactor upon impact after a launch abort, during an explosion on the launch pad or after sea immersion (increasing reactivity through water moderating effect) safety rods containing neutron poisoning material (B_4C for instance) are latched in the core, tailored to assure subcritical conditions under these circumstances.

Space power reactor will be operated at power only after achieving a "safety" orbit at an altitude above 600-800 km. From this altitude the time to reach high atmosphere by natural orbital decay is 300-400 years or more, which is by far sufficient to bring the radioactivity down to acceptable level (1).

In case of early accidental reentry, even if unlikely, intact reactor landing is prefered to dispersion in high atmosphere. For an intact reentry the reactor could more easily be localized, radiation hazard minimized and safeguarding of fissile material enhanced (one hundred kg of fully enriched uranium).

In orbit the confinement of the radioactive fuel in the reactor vessel in case of cooling accident and any other accident can be assured by an appropriate design.

Another event to consider is the hypervelocity collision with space projectiles as natural micrometeoroids or artificial space debris. These impacts can

produce serious structural damages to the nuclear power system and accelerate the orbital decay rate of the spacecraft.

IV - Overview of the ERATO concepts

A space nuclear power system consists of (fig. 1) :

- a nuclear reactor cooled by gas or liquid metal which is the heat source of the system.

- an energy conversion system which produces electric power from nuclear heat carried by the coolant.

- a radiator wich is the heat sink of the system and radiates in space the nuclear heat not transformed in electricity.

- a shield to protect payload and sensitive equipments from neutron and gamma photon irradiation.

In space the waste heat rejection system is a radiator the area of wich is restricted by the fair capacity of the launcher. The available area for a non deployable radiator afforded by the Ariane V geometrical features is about 180 m^2

Therefore 140 m^2 only are alloted to the power system radiator, in order to save a sufficient area for the payload and auxiliary device radiators.

To supply a 200 kw electric power using a 20 % efficiency conversion system, the thermal power to reject in space is about 800 kw. With a 140 m^2 area, the radiator must operate in a high temperature range, from 550 (inlet) to 250°C (outlet) in the 200 kwe ERATO concept. Under these conditions to achieve a 20 % efficiency the nuclear reactor, which is the heat source of the system, must operate above 1100°C. It needs a very high temperature liquid metal reactor technology, not available to day, consisting in a lithium cooled and UN fuelled fast neutron reactor, with Mo-Re alloy as structural and cladding materials (2). Figure 1 gives a general view of the UN-Li-MoRe 200 kwe power system.

The reduction of the power level from 200 (for electric propulsion) to 20 kwe (for a space based radar or a lunar base) with the same radiator area available (up to 140 m^2) permits to consider lower heat source operating temperatures. This extends the range of applicable technologies (materials and techniques) to more conventionnal technologies and needs a more limited development effort. Such are the technologies of the Liquid Metal Fast Breeder Reactors (LMFBR) and High Temperature Gas cooled Reactor (HTGR) on which two of our reference systems are based :

- a gas cooled epithermal reactor with UC_2 fuel particle bed and superalloys (HRA) as structural materials (Hastelloy X for instance) with a core exit temperature gas of 820°C (3) (fig. 3).

- a sodium or sodium potassium (NaK) cooled UO_2 fuel fast neutron reactor with 316 stainless steel material operating at maximum temperature of 700°C (3) (Fig. 4).

The 200 and 20 kwe considered generators employ a Brayton cycle energy conversion system with He-Xe working fluid. The gas is heated through a liquid metal-gas heat exchanger in the 200 and 20 kwe liquid metal cooled reactor systems (Fig. 5) and directly in the reactor core in the 20 kwe gas cooled reactor system.

Four Brayton turboelectric converters (gas turbine, compressor, alternator) working in parallel at half nominal rated power are intended in the 200 kwe power system (one or two in the 20 kwe unit) to permit a back up operation at quasi nominal power in case of conversion unit partial unavailability and improve the global system reliability.

After working in the turbine, the gas flows through a heat recuperator intended to increase the cycle efficiency, before cooling in the radiator. The radiator is either a gas tube radiator directly coupled to the He-Xe loops (20 kwe power system), either a mercury heat pipe radiator (200 kwe power system), the evaporator of which is heated by He-Xe. To improve the system reliability heat pipe radiator is also envisaged for the 20 kwe power system in spite of a mass increase. Radiator is manufactured in beryllium or aluminium alloy according to the working temperature, and coated with a high emissivity material.

A shadow shield located close to the reactor reduces the irradiation of payload and spacecraft sensitive equipments (instrumentation, power conditionning, computer, reactor control drum actuators...) by fast neutrons and gamma photons. The shield is designed to restrict the fast neutrons and gamma doses to 10^{13} n/cm^2 and 0,5 MRad at a distance of 20 m from the reactor over a lifetime of 7 years. Shielding materials (LiH and B_4C) are arranged within the shield so as to meet the dose criteria with the minimum shielding mass and an operating temperature compatible with absorbing materials.

The start up in orbit of a liquid metal (Li ou Na) cooled reactor with frozen coolant needs a special procedure based on nuclear heat thawing of the core followed by electrical heating of the primary piping and heat transport from the reactor to the heat exchanger by a lithium by-pass circuit.

The substitution of the NaK eutectic, liquid at room temperature for sodium in a 20 kwe power system releases the contraints and the uncertainties of the frozen coolant thaw process.

Detailed breakdowns of main characteristics of 200 and 20 kwe power systems are given, in Tables I and II, among which the total system mass : about 2200 kg for a 20 kwe sodium cooled concept and 6000 kg for a 200 kwe lithium cooled concept.

V - Development program - Conclusions

Quantitative assessments of the lead time and cost required for the development have been performed for each concept.

The development of a space nuclear power system cooled by liquid metal as sodium or Nak, using amply available technologies of Liquid Metal Fast Breeder Reactor could be achieved in 10-12 years without important technical risks at a lower cost. A such concept is not limited to a 20 kwe electric power but can be extrapoled up to 45 kwe if using the maximum radiator area offered by Ariane V features.

On the other hand a some hundred kwe power system using a nuclear reactor operating at more 1100°C needs very high temperature materials (as MoRe alloys) and technologies (tubormachine for instance) which are not available to day. The development of a such system will be longer, about sixteen years, more expensive and with significant technological risks.

In all cases a ground demonstration station must be built, for tests in conditions as near as possible to the in orbit conditions, including a nuclear reactor prototype directly coupled to a heat sink and an electrically heated version of the entire system.

Considering CNES and CEA experience in space and nuclear fields it would be possible to develop in France a space nuclear power system if it was decided so. But there is no envisaged mission up to now requiring such electric power neither in France, nor in Europe moreover. Nevertheless development of high electric power system which represents a new milestone in the conquest and utilization of space constitute a very long process. To be ready for launch in years 2005-2010, an active development programme must be undertake without further delay, which could be conducted with in the frame of an european or international program. The Mars exploration mission or the manned lunar base envisaged at he beginning of next century could be opportunities for a such collaboration In the last case concept can be simplified because lunar gravity and possibility to assembly in situ a large modular radiator and to use lunar material for the neutron shielding.

Acknowledgments

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COMPONENT	UN-Li-MoRe 200 kwe	UO_2-Na-SS 20 kwe	UC_2-HeXe-HRA 20 kwe
Reactor			
Thermal power (kw)	1100	110	125
Uranium (93 % U_{235}) mass (kg)	113	70	137
Fuel	UN	UO_2	UC_2
Structural material	MoRe	S.Steels	Superalloy
Primary coolant (P kPa)	Li (200)	Na (250)	HeXe (800)
Core inlet/outlet T°C	1147/1197	577/682	511/820
Control drums ($Be+B_4C$)	12	12	12
Safety rods (B_4C)	7	7	19
Shield	B_4C+W+LiH	B_4C+LiH	B_4C+LiH
Intermediate heat exchanger			
Gas inlet / oulet T°C	733/1127	430/670	
Brayton turboelectric converter			
Turbine inlet T°C	1127	670	819
Turbine inlet pressure (kPa)	1000	900	780
Compressor inlet T°C	260	59	118
Compressor pressure ratio	2,25	2,06	2,16
Radiator			
Power (kwt)	820	80	104
Inlet/outlet T°C	567/260	236/53	368/119
Area (m^2)	140	86	54
Global system efficiency	0,18	0,18	0,16

Table I : Main Characteristics of ERATO Systems.

Component	UO_2-Na-SS 20 kwe	UC_2-HeXe-HRA 20 kwe	UN-Li-MoRe 200 kwe
Reactor	375	527	480
Shield	240	370	950
Primary system	90		500
Conversion system	186	151	1290
Main radiator	430	281	1800
Equipments-Structure	876	771	980
Total System Mass (kg)	2197	2100	6000
Specific Mass (kg/kwe)	110	105	30

Table 2 : Mass (kg) summaries for 20 and 200 kwe turbo-electric power systems

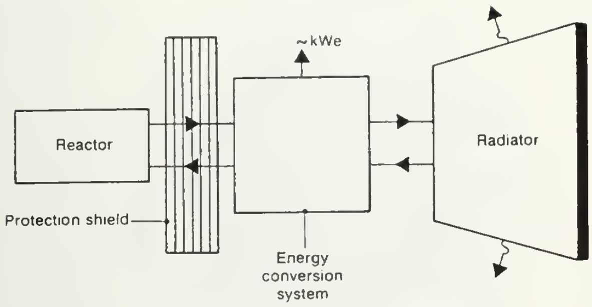


Figure 1 : Schematic diagram of a nuclear space power system.

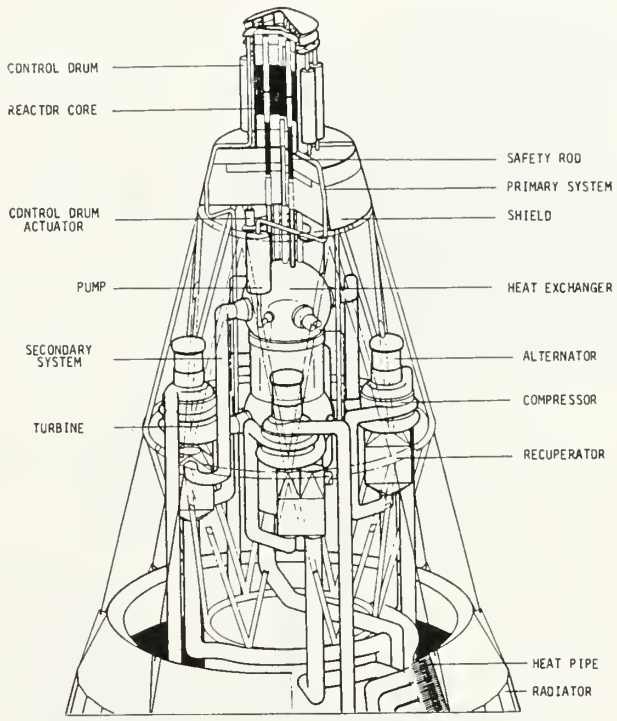


Figure 2 : Lay out of the 200 kwe nuclear Brayton space power system.

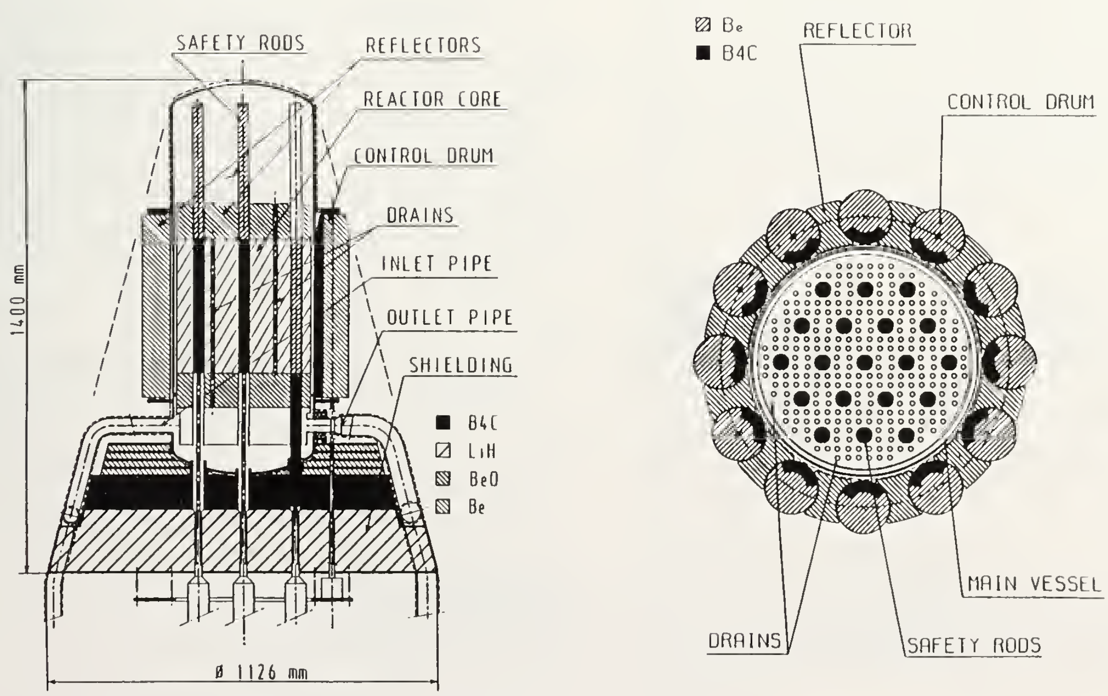


Figure 3 : UC_2/HeXe/HRA 850°C concept: vertical and horizontal cross sections of the reactor block.

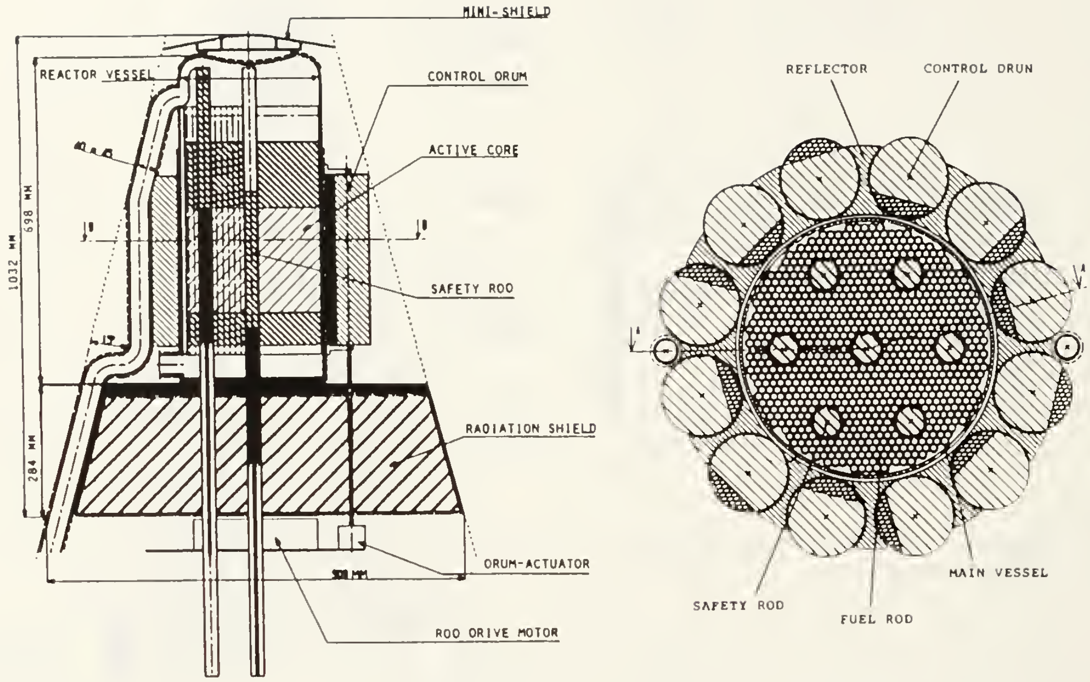
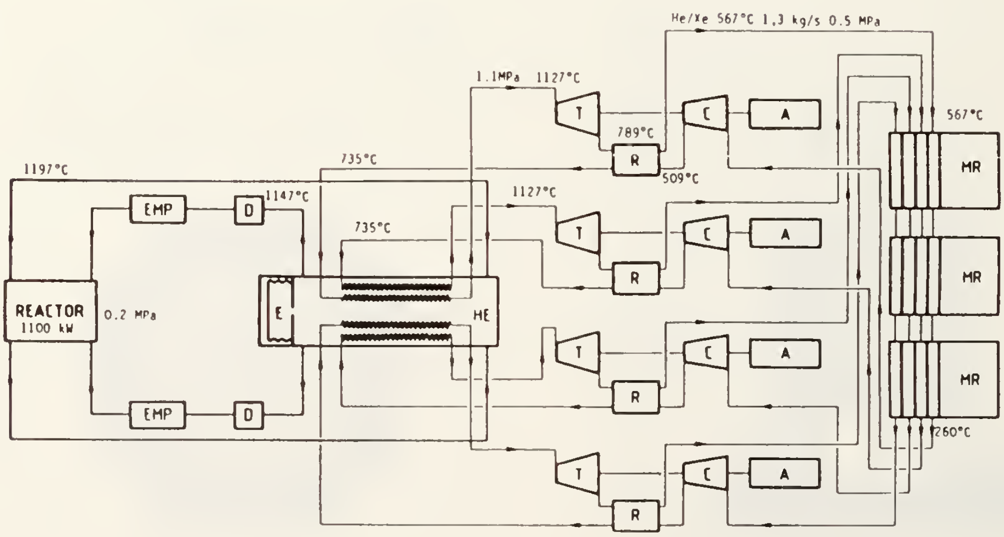


Figure 4 : UO_2/Na/SS 700°C concept: vertical and horizontal cross sections of the reactor block.



A : Alternator (55 kWe x 4)
T : Turbine (He-Xe, 1.3 kg/s x 4 1.1 MPa)
C : Compressor (CPR ~ 2.3)
R : Recuperator (590 kWth, η ~ 0.8)
EMP : Electromagnetic pump
D : Flowmeter (Lithium, 2.7 kg/s x 2 0.2 MPa)
E : Lithium expansion device
MR : Main radiator (820 kWth/140 m²)
HE : Heat exchanger (1050 kWth)

Figure 5 : Redundant Brayton Turboelectric Converter Arrangement in the 200 kwe ERATO reference Project.

SPS 91

C1.4 Increasing the power of microwaves using concentrated sunlight

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ABSTRACT

The paper describes a power satellite concept which an electromechanical device might be able to convert sunlight more efficiently into microwave energy by a direct process, while maintaining cost savings. The concept comprises of a refractor which can be folded, a piston system which has greater mechanical advantage and a microwave resonant cavity. The refractor focuses sunlight onto the movable piston system. The piston system compresses the microwave field in the cavity alternatively. The high-power microwave output is beamed to earth from a transmitting antenna. The generation of appropriate microwave power from the device would be at least 90% efficient and transmission through space is almost lossless. Array of the device can be assembled in space to produce greater output. This concept makes available lighter, more efficient and is far easier for construct than those using present technology.

RESUME

La communication décrit un système de puissance de satellite de nature électromécanique, capable de convertir le rayonnement solaire en microondes plus efficacement pour un procédé direct tout en restant économique. Le concept est constitué d'un concentrateur qui peut être plié, d'un piston préférable mécaniquement et d'une cavité résonnante à microondes. Le concentrateur concentre la lumière solaire sur le piston mobile qui comprime le champ de microondes dans la cavité d'une manière alternative. Le faisceau de microondes de grande puissance est transmis vers la terre par une antenne. La génération d'une puissance appropriée de microondes par ce système serait d'une efficacité d'au moins 90 % et la transmission à travers l'espace est presque sans perte. Un panneau d'appareils peut être assemblé dans l'espace pour augmenter la puissance. Le concept s'avère plus léger, plus efficace et plus facile à construire que ceux de technologie courante.

KEYWORDS

Electromechanism, microwave cavity, super conductivity, transmission fluid, achromatic refractor.

INTRODUCTION

Power satellite concept preludes the need for storage to cope with the intermittency of solar energy on earth surface. The satellite in geostationary orbit collects sunlight to produce microwaves and transmits the latter to receiving stations on earth. The last conversion would be from microwaves to electricity suitable for use.

Prevailing technology advocates solar cells for sunlight-electricity conversion needed to generate the microwaves, but they are highly inefficient and extremely large structures have to be erected in space. The klystrons and magnetrons needed for the electricity-microwave conversion are bulky and are of considerable weight and would increase the mass of payload. Dickinson[1] proposed an innovative concept consisting of an electromechanical device which might be able to convert sunlight into microwave energy by direct process. Its theoretical efficiency is 90%. However, Dickinson's device has some moving parts which could introduce maintenance problems. Using parabolic mirror as the sunlight concentrator could introduce prohibitive cost, moreover, malfunctions due to very high concentration ratios are yet to be overcome.

DESCRIPTION OF THE EMBODIMENT

The new solution is a device comprising of a concentrator which is a refractor and can be folded, a piston which has greater mechanical advantage and a microwave resonant cavity.

The Refractor

Refractors are comparatively far easier to construct and about five to ten times cheaper than reflectors. The refractor is a lens-system. Its folding ability would facilitate easier transportation and refurbishment. The lens-system could be of solid glass or hollow glass forming an array of much smaller lenses. It is made trans parent only to sunlight by applying

appropriate non-reflection or multifaceted "selective" treatment on the surfaces. The most critical factors in the selection of the material of the lens structure are (i) strength, (ii) durability, (iii) non-degradability, (iv) solar energy transmission and (v) cost.

For an array, selecting the most efficient geometry is vital. To achieve achromatic effect, lens G1 is either hollow and lens G2 solid or vice versa. Both G1 and G2 may be hollow or solid but made of differnt suitable materials. (see figure 1). So far as the refractive indices of G1 and G2 are not equal but carefully selected, fine focusing comparable to that of reflectors could be obtained. Hollow lens-system if available, would be lighter and less expensive than a solid one.

Fresnel optics could be very promising and adaptable too with serious research shown.

The Piston System

The force exerted on the piston by the sunlight is increased by applying Pascal's principle of transmission of pressure in fluids. The principle states that when a fluid completely fills a vessel and a pressure is applied to it at any part of the surface, that pressure is transmitted equally throughout the whole of the enclosed fluid.

The pressure p due to the incident solar radiation $\dot{P}$ is

$$p = \frac{\dot{P}}{C}(1 + R) = \frac{\text{Force}}{\text{Area}} \qquad (1)$$

where C is the velocity of light and R the reflectance at piston surface.

Let F_1 be the force exerted on the piston of area A_1 and is equivalent to that of Dickinson's device. Let F_2 be the thrust or force transmitted to the ram of area A_2.

$$p = F_1/A_1 \qquad (2)$$

$$F_2 = p\, A_2\, Z = \frac{(F_1)\, A_2 Z}{(A_1)} \qquad (3)$$

where Z is the efficiency. Assuming Z=1, then

$$\frac{F_2}{F_1} = \frac{A_2}{A_1} \qquad (4)$$

but $A_2 > A_1$. Therefore $F_2 > F_1$. (5)

The force is thus magnified at the ram in accordance with the above principle.

The mechanical advantage is directly related to efficiency, all other factors being the same. Therefore

$$Z_2/Z_1 > 1. \qquad (6)$$

Z_1 is the efficiency of Dickinson's device. Z_2 is the efficiency of this embodiment.

If $Z_1 = 90/100$ then $Z_2 > 90/100$ (7)

Frictional forces due to the piston and fluid motion and internal surface of cavity could cause loss in efficiency. Nevertheless, this embodiment would have efficiency greater than 90 percent.

Transmission Fluid

A complex of special properties is observed in Helium (He II) at extremely low temperatures which makes it suitable to be used as the transmission fluid. However, it is very expensive.

Recent advances in new ceramic-like materials of much lower cost which superconduct at much higher termperatures; easier to reach and achieve compared with the far lower Helium temperatures make way for the use of Nitrogen. Furthermore, Nitrogen is much cheaper than Helium and is about 78% of the earth's atmospheric composition. In bulk form, the transition of these materials to superconductivity starts around 100K. Nitrogen is liquid at 100K. Thus the cavity made or coated with the appropriate ceramic-like material will superconduct when filled with liquid Nitrogen. The presence of the transmission fluid helps to facilitate and maintain the moving piston and the ram at the cryogenic temperatures to ensure higher conversion performance.

Superconducting Cavity

Until the advent of superconductors, electro magnetic radiation could not be contained long enough for it to interact with a mechanical system. The intensity of the microwaves transmitted into the metal would drop rapidly to zero within the limits of this surface layer due to energy losses on Joule-Lenz heat. However, in a superconductor, there is no measureable electrical resistivity, thus losses equal to zero and the reflection co-efficient R of the superconductors with the microwaves equals unity. This facilitates electromagnetic ringing times of milliseconds to even seconds. Hence, no microwave energy is lost through the walls of the cavity; they are contained long enough by the strong superconducting material at cryogenic temperatures for interaction to take place.

Operation

Figure 1 illustrates a cross-sectional view of the embodiment of the invention to show the principle of operation of the device.

When the piston-system is farthest from the cavity end wall W, a low intensity of microwave via the input switch at a frequency resonant to maximum volume V of the cavity is established in the cavity. The superconducting property of the cavity keeps the microwaves resonating. Meanwhile, the concentrated sunlight due to the refractor, forces the piston towards the end of the wall W. The force is magnified at the ram due to the transmission fluid. Greater radiation pressure is highly desired to generate considerable amount of power to oscillate the piston.

Since the resonator is lossless and under adiabatic conditions, the number of photos of microwaves n remains constant. Decreasing the volume of the cavity increases the energy of the microwaves thereby increasing the characteristic eigen-

frequency w. Thus the Eigen-frequency (which is in the radio-frequency range) and the microwave field energy N are proportional to the displacement x of the piston system since the cross-sectional area A is constant. These are in accordance with Boltmann - Ehrenfest theorem from the field of quantum mechanics. The energy density in the cavity would be limited by the maximum magnetic and electric fields sustained at the superconducting surface.

The low-power microwave of frequency w1 input changes into a high-power pre-determined value w2. The eigen-frequency transition takes place in a very short time compared to the electromagnetic ringing time. The w2 is coupled out to the output switch. The switches are frequency sensitive. Input switch closes and output switch opens to permit the exit of high-power output to a transmitting antenna. With the exit of w2 the output switch closes and the piston system is supposed to retreat in theory. However, it is aided by a valve - M, almost imbedded in the ram.

M-valve is fairly magnetised when light of appropriate frequency and intensity falls on it, but it does not affect the super-conductive property of the cavity. It is fixed in such a way that it pushes the ram outwards.

At the pre-determined minimum distance to the end wall W, a light pulsar L synchronised to the piston motion is activated. L sends a light pulse to M. The cavity is blind to the light pulse. M is magnetically enhanced, meissner effect is exhibited between M-valve and the end wall W. This pushes the piston system outwards to its original position, maximum distance from the end wall W. The input switch opens for the cavity to be replenished to keep n constant. The process is repeated. If the compression is repeated at a high rate, a small amount of low-power microwave frequency becomes a large high-power one.

Perhaps, even the device could be self-excited; not needing an external source of low-power input microwaves if the M-valve could be of material which not only exhibit the magnetic property but also emits low-tomoderate intensity microwaves as input, when light incidents on it.

Array of the device can be assembled and may or may not be coupled to each other to produce greater output (see fig 2). A device designed by the same innovator that might booast output in the array is also available.

DISCUSSION

The device converts a low-power microwave input to a high-power (10cm wavelength) microwave radiation and is beamed to earth from appropriate transmitting antenna; one kilometre diameter has been suggested.[3] At the 10cm wavelength there would be negligible atmospheric absorption or refraction and no atmospheric ionization. Thus transmission through space is almost lossless. The generation of microwave power from the device would be of at least 90% efficiency. Some power might be used to maintain stable orbit and communications via commands. The supporting structure could be less dense than needed on earth and would not take up valuable ground space. The modestly low intensity microwave of beam-width of about seven kilometres would be available at all time invaluable of conditions at earth surfaces. Very small fraction of the total power would be released as waste heat into the biosphere at the earth conversion station since microwave-direct current conversion is done with very high efficiencies. In constrast, stations using conventional or nuclear fuels dispose waste heat as much as one and half times the energy put into the power grid.

Challenge

Though, innovative the concept, certain engineering problems must be solved before such a device can be built.

There would be very sharp temperature changes during brief eclipse and power supply would be cut off. The rapid change would cause severe thermal stresses on the whole device.

Another major threat is the incredibly tenuous and hot solar wind. However, there are so few particles per cubic centimetre, thus very small amount of energy is transferred when the solar wind strikes a solid body.

The superconducting of the cavity could be destroyed when sufficiently heavy current is passed through it. Such "disturbing" current are likely to be generated in space during solar flares and heavy sunspot activity. Apparently, more satellites have to be put in orbit to counteract the said dangers, since the chance that larger number at different points would be threatened at the same time is very small.

Stronger refractors with higher concentration ratios, stronger superconducting materials and superior refrigeration system capable of maintaining the cryogenic components for more than 10 years are needed. Means to ward off excess heat from the refractor should not be beyond present-day technology.

The controversy with ecological risk due to low-intensity microwave beam can only be answered by research.

The said challenges and other unaware of, are typical of the type which has been the subject of past research effort and would be faced by future research scientist and engineers.

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APPENDIX

If the microwave energy density $\emptyset$ is accelerated $\vec{a}$ through a displacement x by the Poynting vector S in a time T then

$$\frac{\emptyset \vec{a}}{V} = \frac{S}{T} \qquad (A1)$$

$$\vec{a} = \gamma^2 x \quad \text{and} \quad V = A x \qquad (A2)$$

(A2) into (A1) gives

$$\gamma^2 = \frac{S\,A}{\emptyset\,T} \qquad (A3)$$

System is harmonic with cycilc frequency γ. γ determines the eigen frequency of the output microwave.

At the farthest $V = V_0 + x A$ with decay time T_1, where V_0 is the volume of the initial input microwave. For a lossless resonator the microwave field energy Ω is proportional to the displacement and inversely proportional to the volume, cylinder of the resonator being operated as a TE_{111} mode microwave cavity.

$$\Omega \propto x / (V_0 + A) \qquad (A4)$$

$$\Omega \propto 1/A\ (1 + V_0/Ax)^{-1} \qquad (A5)$$

Applying Binomial expansion to the right hand side of the equation and neglecting higher powers

$$\Omega = \chi \left\{ 1 - V_0/Ax + (V_0/Ax)^{-1} - \dots \right. \qquad (A6)$$

χ is a constant.

During compression with charging Time T_2 till the minimum volume $V = V_0 - x A$

$$\Omega \propto x / (V_0 - x A) \qquad (A7)$$

$$n \propto -1/A\ (1 - V_0/Ax)^{-1} \qquad (A8)$$

Applying Binomial expansion to the right hand side of the equation and neglecting higher powers

$$n = -\chi \left\{ 1 + V_0/Ax + (V_0/Ax)^2 + \dots \right. \qquad (A9)$$

The negative sign agrees with equation A3 that the system is harmonic and the microwave field energy is directed towards the centre of oscillation. Good selection of A, V, S, w, the electric and magnetic fields which can be sustained at the superconducting surface, will increase the rate of compression of cavity.

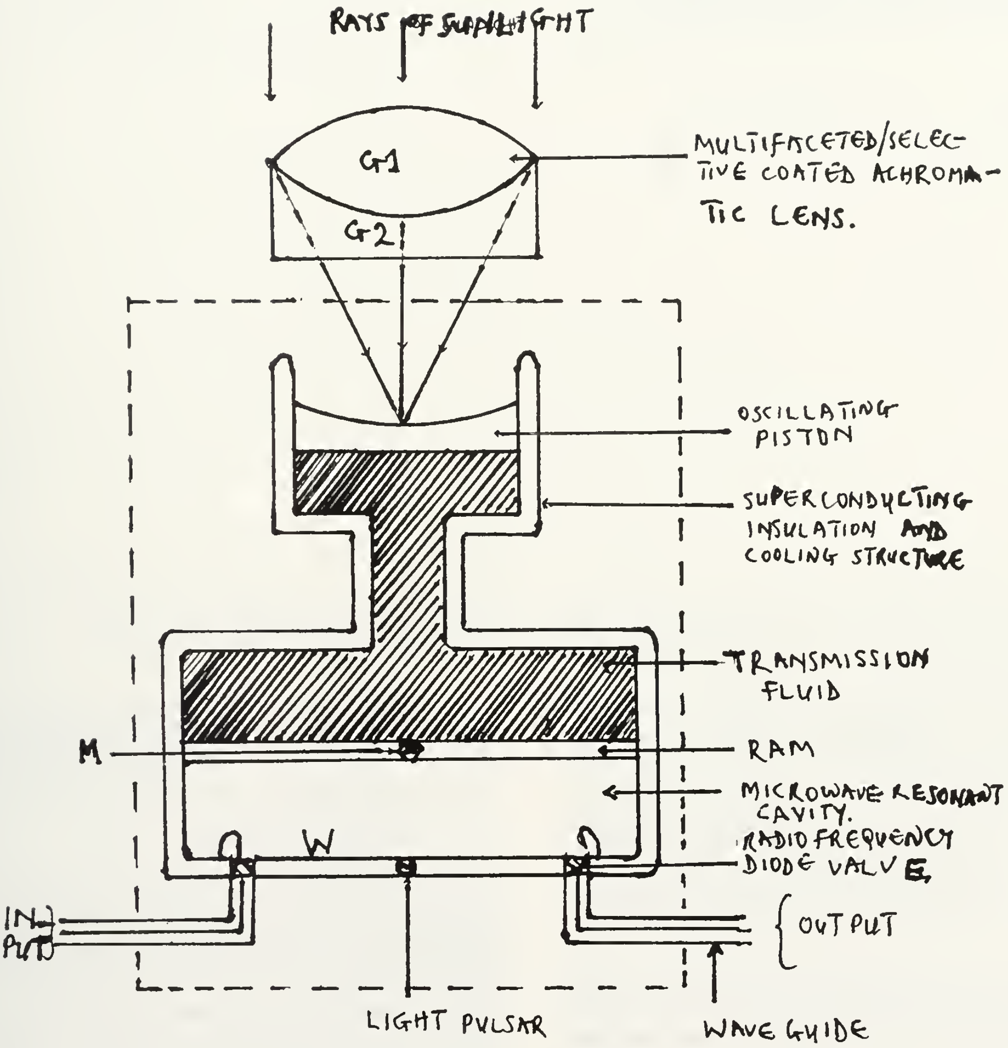

Figure 1.

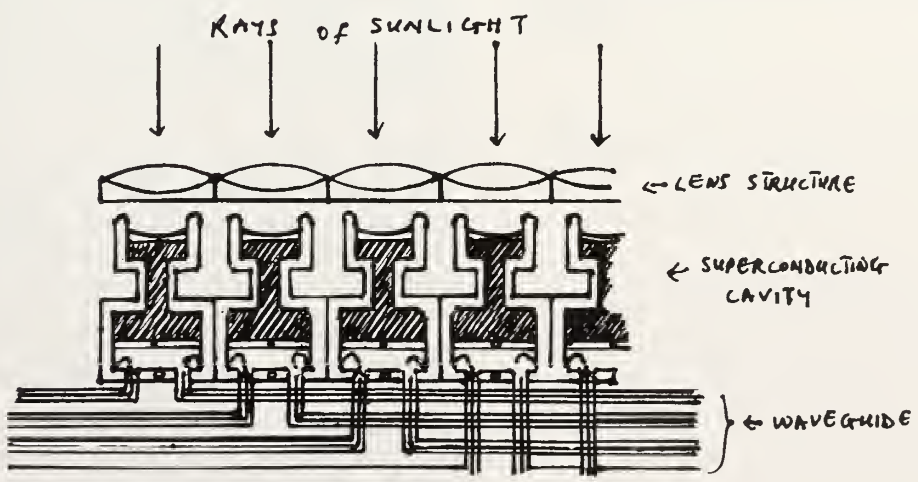

Figure 2.

C1.5 Space Solar Power Program (SSPP) design project for the international space university 1992 summer session in Kitakyushu, Japan

G.E. MARYNIAK - Space Studies Institute, Princeton, USA
T.B. HAWLEY - International Space University, Cambridge, USA

This presentation outlines a proposal for a design project to be conducted at the 1992 Summer Session of the International Space University, (ISU 92), which will take place during July and August of that year in the city of Kitakyushu, Japan.

The International space University has conducted five design projects during its first three Summer Sessions. The inaugural ISU session, held at the Massachusetts Institute of Technology in 1988, featured the design of a lunar base to support Solar Power Satellite Construction, as the first ISU design project. Subsequent projects have also been relevant to the solar power satellite project. In addition, the concept of large scale space solar power as well as traditional uses of space power for exploration, propulsion and bases are part of the ISU core ans advanced curricula.

The design project proposed for the 1992 session will have the following elements :

- Multi-disciplinary design study, to include financing, management and legal issues

- Multi-national student and faculty approach

An advisory committee for the project is being created under the chairmanship of Dr. Peter E. Glaser. Faculty for the project will include a broad range of leaders from academia, Industry ans government agencies from around the world.

see paper a 7.5 p 305

C1.6 Economics analyses of lunar resources for Solar Power Satellites

G.R. WOODCOCK - Boeing Aerospace & Electronics, Huntsville, USA

Several studies have determined that almost all, (eg. 95 to 99%), of a Solar Power Satellite (SPS) could be produced from lunar-derived materials. It is argued that in view of the Moon's much smaller gravitational potential, transportation costs to deliver lunar materials to geosynchronous orbit would be much less than to deliver materials from the surface of the Earth to geosynchronous orbit. Very preliminary cost calculations tend to substantiate the possibility of reducing SPS cost via the lunar materials route, but more substantial calculations are needed to assess the economic viability of lunar resources and transportation operations for SPS. The proposed paper will describe the appropriate methods and illustrate them with representative calculations using best available estimates from key economic parameters.

This paper will extend results of an earlier paper (1989) investigating economics of lunar resources for SPS, and also extending methods and results of a 1990 paper (presented at Case for Mars IV) on economic factors relating to space settlements. In the first reference, I used a 120-parameter static input/output model of a space transportation network. Significant additional understanding can be derived by extending the input/output model to include mining and manufacturing operations on the lunar surface and in GEO orbit and by making it dynamic in order to model the build-up of the lunar industry that would produce the SPS materials.

The key issue here is productivity. The Case for Mars paper developed a rudimentary dynamic model (12 parameters) which indicated that very large advances in productivity, meaning major advances in space robotics, are necessary. Our lunar base needs to have productivity about like a Japanese automobile factory.

For the proposed paper, I plan to expand the Case for Mars IV model to about 50-75 parameters, merge it with the transportation network model, examine some transportation alternatives (rockets vs. mass drivers), examine productivity factors, eg. manhours per pound of manufactured products, and consider different mixes of Earth vs. lunar products.

see paper a 3.7 p 194

C1.7 Liquid Metal Magnetohydrodynamic (LMMHD) converter for space power system

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ABSTRACT

The liquid metal MHD or (FARADAY) Converter is a conversion system which allows to produce electricity from thermal energy without any moving solid part. Then, such a system is very attractive in space where a long life time is required. The basic principle of the process is the expansion of a gas to accelerate a high temperature liquid metal in a MHD generator where this liquid metal interacts with a magnetic field to produce electricity. By using an inductive generator the electric current can be delivered directly on the alternative form with adjustable voltage and frequency.

RESUME

La conversion MHD à métal/gaz (ou Conversion de Faraday) permet de produire de l'électricité à partir d'une source chaude sans aucune pièce mécanique mobile. Un tel dispositif paraît séduisant pour une application spatiale nécessitant une grande fiabilité. Le principe de base utilise la détente d'un gaz pour communiquer de l'énergie mécanique au métal liquide. L'interaction de ce métal liquide avec le champ magnétique délivré par un inducteur permet de produire de l'électricité. En utilisant un générateur à induction l'électricité peut être délivrée directement sous forme alternative à tension et fréquence ajustables.

1. Introduction, main principles.

Liquid MHD generators offer a mean of direct conversion of thermal energy into electrical energy. The main principles (fig. 1) of the process [1] adopted for space power systems are the following :

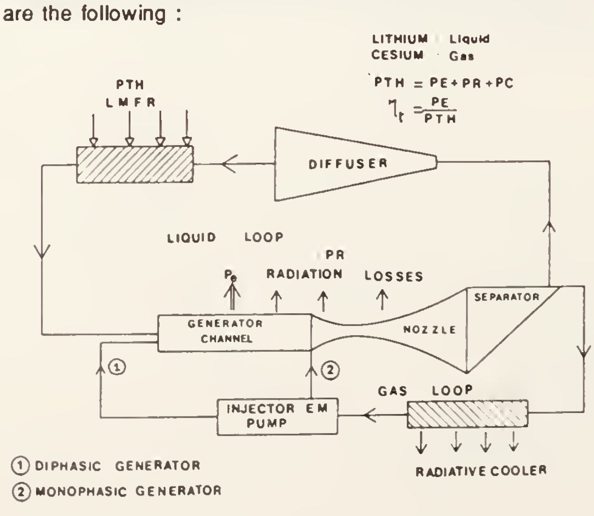

Fig. 1 : Schematic representation of LMMHD Loop

The expansion of a gas injected into a high temperature liquid metal flow allows to convert thermal energy (transported by the metal) in mechanical energy. Due to the fact that the gas is continuously in contact with heat source which has a very great heat capacity this expansion is quasi isothermal. Later on, the two phases are separated. Then the liquid metal converts a part of its kinetic energy in potential energy by circulation in a diffuser, it is reheated by circulation in the hot source of the process which can be for example a fast breeder nuclear reactor. The electricity is produced in the generator channel and results from the interaction of the liquid metal flow with the magnetic field of an inductor.

After separation from the liquid metal, the gas is condensed in the cold source which must be, in space, a radiative cooler. Then, it is vaporized, after pumping by an electromagnetic pump, before its reinjection in the liquid metal flow at the inlet of the nozzle which is the motor of the global process.

2. Mechanical to electrical energy transfer

The conversion of the mechanical energy into electricily [2], [3], [4] in the generator can be obtained by two different ways :

a) the conduction process (fig. 2) makes use of either a constant or a low frequency magnetic field. The electric current perpendicular to both the magnetic field and fluid flow directions, is collected by two electrodes placed on the lateral walls of the MHD channel. This type of transfer involves low voltage (1V)and high current intensities (several thousands Ampere) and needs to be adapted to the characteristics of the load. Nevertheless, the overall simplicity of the apparatus, the well-known flow field and its good electrical efficiency are some of its advantages.

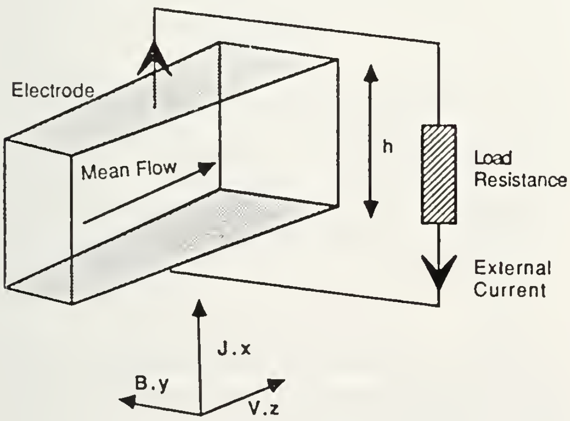

Fig. 2 : MHD Conduction Generator

b) the induction process (fig 3) makes use of sliding magnetic fields produced by inductors analogous to those used in linear machines (e.g. electromagnetic pumps, linear motors...). The electric current is created by direct magnetic coupling between the liquid metal vein (the induced circuit) and the windings of the inductor. The overall method may be described as follows : if the flow velocity is less than that of the field (synchronous velocity), the electromagnetic forces are motive (cf. electromagnetic pump). Electrical energy is converted into mechanical energy. On the other hand, if the flow velocity is greater than the synchronous velocity, the electromagnetic forces are resistive (i.e MHD generator) and mechanical energy is converted into electricity. As distinct from the conduction process, for which permanent magnets may be used, here, the inductor must be fed by an electric current. This energy source can be external to the system or internal. In the latter case, part of electricity energy generated can be used to maintain the induction field. This is what we refer to as self-excitation. The electric current needs a capacity bank on each of the three phases to produce the self oscillation which depends of the relative value of the capacity inductance and load of the machine connected with the generator.

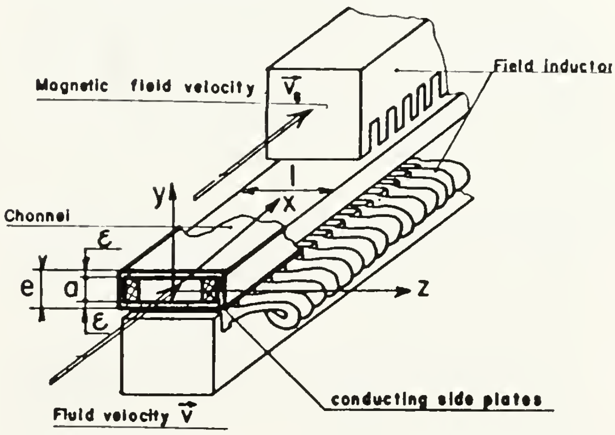

Fig. 3 : MHD Induction Generator

Such a process presents three Important advantages :

(i) it does not need electrodes to collect the induced current
(ii) electricity is delivered directly in the form of alternating current with adjustable frequency and voltage
(iii) it can work without electric external source and then is well adapted to the utilization in space.

3. Thermodynamic aspects

The thermodynamic cycle [5] described (fig. 4) by the gas is on the Rankine type and exhibit a quasi-isothermal expansion after vaporization ; it gives a very great thermodynamic efficiency which can reach, using regenerative heat exchanger, more than 90 % of the Carnot efficiency.

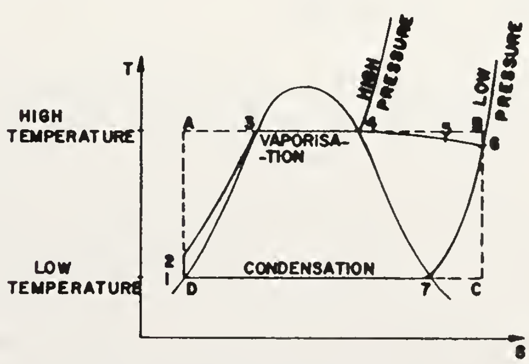

Fig. 4 : LMMHD Rankine Cycle

In space conditions which need a cold source at a relatively high level of temperature (800 to 1000 K) and then a hot source around 1400 K, we must use a second metal as thermodynamic fluid to reduce the pressure level at high

temperature of the cycle. Then the global working conditions of the process need the utilization of two metals, one as thermodynamic fluid and the other as conducting fluid. This two fluids must be immiscible and chemically compatible. The best choice seems to be the lithium as liquid metal and the cesium as thermodynamic fluid. Then we have adopted such a couple to perform the working conditions of a liquid metal MHD convertor in space.

The global properties of such a convertor using an inductive process to produce electricity is the following :

- It does not need any moving mechanical part and then its reliability is very good.
- It's global efficiency is great and allows to reduce the size of the radiator which is the main part of the size and weight of the global system
- The liquid metal (i.e. lithium) could be the same as the one used to cool the reactor, allowing to reduce the difficulties in heat exchanges from the reactor to the converter.

Moreover the system is self adjustable to the external level of power.

4. Numerical Simulation

A code (fig. 5) based on global balance equations has been developed to estimate the mass, size and efficiency for each part of the converter. This code is very flexible and permits future modifications and improvments. Iterative methods are used in order to optimize the mass or the energy efficiency of the various components of the converter.

The procedure that is used for calculating a converter with a radiative cooler is as follows :

We enter the available output electrical power P_{up}, the lithium mass delivery, Q_l, and the hot source temperature, T_H. Then, we use an external iteration loop where the Cesium mass flow rate, Q_g, acts as central parameter. The gas expansion has to give all the mechanical power for the circulation of liquid metal on the whole converter loop. Indeed this power must be equal to the electrical power needed for the pumping on the delivery, plus the available output power added to the power losses in each element. The losses and therefore the geometry of each element are directly linked to the gas delivery. The calculations are developed in the following way : we start with some initial value of the various losses ; we also choose an initial value for the cold source temperature, T_C. From the analytical expression of the cesium saturation temperature [6] we obtain the maximum and the minimum values of the cycle pressure. Then the gas unitary mechanical power P_{GV} is computed from the enthropy ΔS and enthalpy ΔH variations during the almost isothermal gas expansion

$$P_{GV} = \Delta H - T_H \Delta S$$

from another source

$$P_C = P_{up} + P_{pump}$$

The electrical power is equal to the available output power plus the power needed for the pump supply. Then if we call ΔP the amount of loss, we can express the cesium delivery as

$$Q_g = \frac{P_c + \Sigma \Delta P}{T_H \Delta S - \Delta H}$$

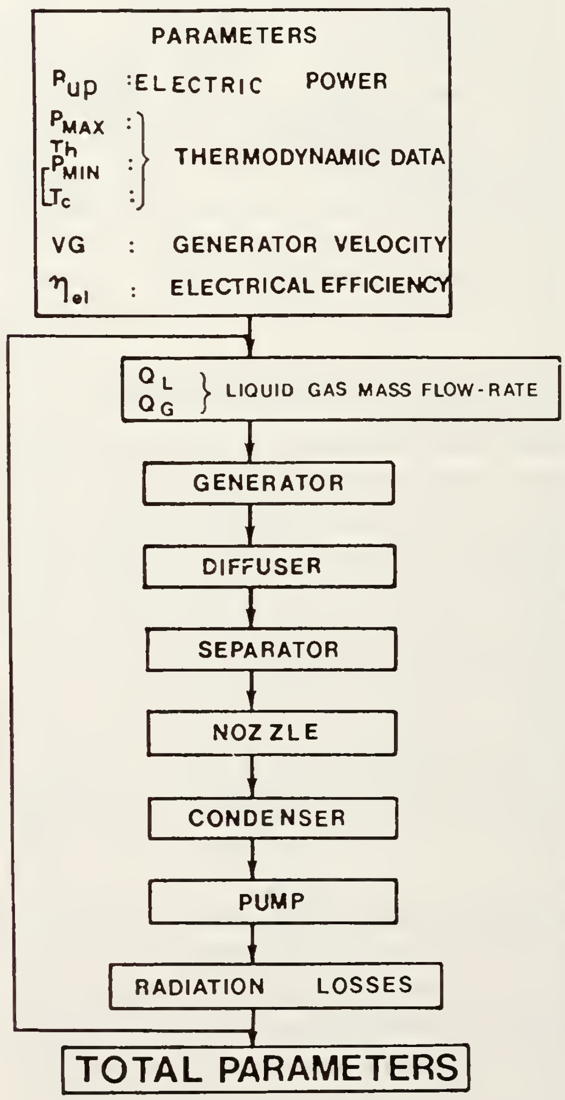

Fig. 5 : Flow Chart of Numerical Simulation of an LMMHD Convertor

In the outer loop our code works out again the various losses until the value of Qg converges. From the value of Qg and the different intermediate hypothesis we can deduce all the characterisitic of the converter and the working conditions and efficiencies. As an example of the global performances of the process we give the main result obtained for a high temperature equal to 1353 K a low temperature equal to 990 K and an output electric power of 200 kWe. We find a global mass of the converter of order 2300 kg with a total efficiency equal to 15 % which is 55 % of the Carnot efficiency, and a specific mass of order of 11kg/kWe.

5. Conclusions

The LMMHD appears as a very attractive process to convert thermal energy into electricity due to its good efficiency and reliability. This kind of converter needs further efforts to develop both theoretical and technological aspects in order to permitt the building of a complete prototype. It seems that its effective interest in space is located in the field of high temperature range (greater to 1100 K) and mean to high power level (greater to 50 kWe).

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C1.8 Power from Space in very natural way

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It has been proposed by several scholars both of the past and of our space age to deliver an additional amount of solar energy in the form of natural light using orbital reflectors.

As in other forms of obtaining power from Space, it is necessary to build large structures in orbit. The great impulse in the designing of such apparatus gave an announcement of international Solar Sail Cup Columbus 500 to commemorate the discovery of the Americas in 1992. In addition to Solar Sail spacecraft designing, all teams were encouraged to propose scientific and applied experiments. One of them was named "Novey Svet" (meaning, in Russian, both "New World" and "New Light").

It was designed by the Space Regatta team in Kaliningrad, Moscow region. Indeed if a Solar Sail spacecraft (here called Solarcraft) is built it would be a perfect reflector : large, light and controllable.

Two main problems are to be solved : how to deploy a thin film structure of several hectares (eg. 2 - 3 x 10,000 m2) in area and how to control so large a structure as to point it to a certain place in the sky or on Earth.

The paper deals firstly with these problems, and then describes what characteristics it would be possible to obtain from such a Space Reflector and what orbits should be deployed to illuminate the Earth during nights including polar nights.

Then an experimental system is described that would be able to deliver sunlight to different places on Earth. Preliminary economical figures are given. In conclusion, some aspects of using such a system are considered. The perspective of it is discussed.

Now an international consortium of enterprises is formed to design and build Solarcraft and Solar Reflectors.

C1.9 Mission to save Planet Earth

J. SVED & P.W. SHARP - ERNO, Bremen, FRG

RESUME

L'Agence Spatiale Européenne a demandé récemment aux équipes d'étude de projets futurs des principales compagnies travaillant pour l'espace d'apporter leurs contributions à la revue des diverses études ordonnées par IESA, portant sur l'infrastructure spatiale habitée Européenne. La portée n'en était pas limitée. Ce papier rassemble les vues de l'équipe des études futures d'ERNO. La préoccupation première est de définir le but véritable d'une infrastructure spatiale industrielle - "mission pour sauver la terre". Les applications industrielles majeures de l'espace sont passées en revue et les moyens permettant de progresser vers cette possibilité sont discutés.

SUMMARY

The European Space Agency recently asked the major space companies future projects study teams to contribute their views to a review of the various ESA commissioned studies related to the European Manned Space Infrastructure. The scope was unrestricted. This paper summarizes the view of the ERNO future studies team. The primary concern is the true goal of an industrial space infrastructure - "Mission to save planet Earth". Major industrial applications of space are reviewed and the means of building towards this capability are discussed.

INTRODUCTION

The European Space Agency Long Term Planning Office has commissioned a range of studies focused on specified functional elements that are perceived to be the building blocks of a space infrastructure where crews based on a space station in Low Earth Orbit are an integral part of the future space applications. The primary function of an initial European Manned Space Infrastructure (EMSI) is to provide a sustained manned presence in Low Earth Orbit. This is basically a space station and a transportation system to ferry crew and logistics material. The first steps in this direction are the Spacelab experience and the current Columbus and Hermes projects. The follow-on from this beginning is today quite uncertain. The configuration of a European Space Station and its functions and services are a matter of technical debate about the results from the completed EMSI studies.

All concepts of the initial infrastructure are major projects that require development of one or more new orbital modules. A large functional space station will be assembled from modules that are sized to fit the capabilities of the available launcher system; Ariane 5. In addition to permanent on-orbit facilities, new transportation elements are necessary for the logistics demands of a sustained habitat. Assured Crew Return to Earth capability requires an appropriate "lifeboat" vehicle.

The utilization of such an initial space station has been assumed to be as a microgravity laboratory to follow on from the Columbus missions. Technology would also be demonstrated through routine operation. All this is well known from the NASA and Soviet manned spaceflight experience.

The above justification for the large expenditures that are mandatory for EMSI concepts is not satisfactory. The question of "where and when is space research going to provide the big return on investment ?" has not yet been answered by the collective European space agencies.

LESSONS LEARNED

The collection of lessons learned anecdotes was a focal aspect for the three industrial teams of this "ESTEC Working Days" (EWD) support study. The categories covered were the various EMSI element studies, successful and unsuccessful programmes of all space faring nations, the degree of new technology needed and the politic factors. Constructive criticism to the European approach was invited by ESA.

The views expressed here do represent a broad consensus in the aware space community. This paper is therefore a technical view of the strategic problem for space industrial development.

The EMSI element study results represent possible solutions for individual functions but they do not form a coherent solution for a future station system and configuration. Almost every aspect of developing and operating such a system or infrastructure has been identified. The early LTE and STEAMS studies which identified scenarios and overall architecture are now regarded as dated and not a solid reference for EMSI.

The EMSI studies reflect a typical U.S. Space Station Freedom approach for servicing and logistics. The crew transport element (Hermes Space Plane) does not remain

attached to the ESS for the period of the mission and therefore a "lifeboat" vehicle is necessary.

A "Columbus approach" has been used for down load under-capacity by using costly planned destructive re-entry rather than re-use of serviceable system and payload hardware. This incoherence has been caused by the Hermes Space Plane system inadequate required volume, and non-recognition of the realistic return to Earth payload requirements to maintain experiment operations. The current Hermes Space Plane configuration is supplemented by an "Escape Vehicle" of capsule configuration in many ESS studies.

The BASE and SAMS studies considered "optimistic", "realistic" and "pessimistic" scenarios based on a fully operational Columbus programme with high user/payload traffic and a European logistics transport infrastructure. The latter is seen to be the most critical aspect. Not only delivery capacity but also reverable down-load mass and volume will have a big influence on the logistic requirements. Mitigating strategies such as onboard sample evaluation, reduction of experiments, small "space mail" system and wasteful controlled destructive re-entry of equipment are all disincentives for an ESS.

Most of the EMSI studies only considered the initial infrastructure defined as a completed Phase 2 (i.e. Autonomous European Space Station). The HABEMSI study also looked at Phase 3 evolution. It also focused on Man in Space research rather than materials science. The Phase 3 scenario included an international return to the Moon and onward expansion to Mars. Launcher performance on the 30 to 60 ton range was identified along with an improved crew and logistics transport.

Element studies such as HOUSE and ICE yielded development costs in the region of 1 BAU per new element. This includes the specific technologies characterizing the elements' function. Human factors technology and architecture are often identified focal points. Comparisons with USA and USSR space stations has provided many valuable lessons.

Case histories of various transportation system projects show many that failed through cancellation. The peril of a repeat with the current big three European efforts cannot be ignored. They were originally initiated as individual programmes and not as part of a planned overall integrated infrastructure. The necessary coherence has not yet been achieved! A central authority for the infrastructure could have prevented these problems by defining all the necessary elements and establishing the requirements in a coherent form. A lack of a strategic goal inevitably leads towards erosion of the system as is currently seen with Space Station Freedom.

STRATEGIC GOAL

The previous argument has great strength when the strategic goal of space exploitation is defined. We advocate Lunar based space industrialization and scientific exploration of the Solar System.

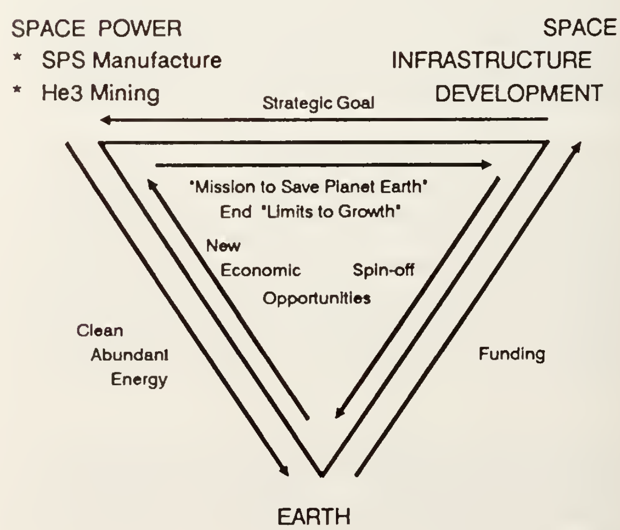
The Japanese long term space goal is focused on the moon as an industrial base. The series of US commissions on space goals have been less able to define a clear goal statement. "Mission to Planet Earth" has correctly won political support in order to enhance our measurement of the global ecosystem. Unfortunately the development of space services to mitigate adverse global climatic change are not strongly publicized by the Space Exploration Initiative. The pro Space Lobby however is aware of the industrial potential of cis-Lunar space but they continue merely to lament their lack of Public relations success.

One recent exception has been the non-NASA advocacy of cheaper technologies to establish a Lunar Base. The extent of Lunar surface operations technology research in the USA, since the Apollo missions, has produced a very significant database of potential mining and construction technology. The Moon is not barren in terms of its potential as a source of raw materials including volatile elements. Mining and refining operations that would sustain modest initial lunar base and transport needs are a tiny fraction of terrestrial equivalents. The mass of equipment to be delivered to the Moon is compatible with Earth Moon ferry vehicle concepts.

The return on investment for the above indicated infrastructure is manifold. There are many spin-off class benefits but the strategic goal is much more precise: Electric power on Earth derived from space industry. The most well known option is the Solar Power Satellite concept. More recently the abundance of Helium 3 isotope in the Lunar regolith has been determined and its potential as the clean fuel for nuclear fusion power generation has been published. Both options rely on raw materials obtained from the Moon.

The lead time for practical nuclear fusion power is usually stated as 20 to 50 years. This must be a function of the investment of government funds into this technology. During the 1980s such government support for alternate energy sources declined as the fear of energy shortages declined.

Figure 1 Industrial Space Infrastructure Strategic Goal must form a part of a credible economic system as represented below.



Today the fear of adverse global climatic change is increasing. The greenhouse effect is common knowledge. Combustion based power is the prime contributor of greenhouse gases. The nuclear fission power industry argues that a great increase in the number of nuclear power plants will help. However there is a public fear of devastating accidents which are more probable with the proliferation of nuclear fission power plants, their dangerous fuel recycling and waste disposal.
Public fear of environmental decay, reduced living standards or never to improve standards in the third world can be harnessed. Space exploitation offers at least two credible means of greatly mitigating the global energy and climate problems. The space industry has a measure of support but it is vulnerable to other issues which command a greater sense of fear with the politicians. The nuclear power industry already has a strong lobby and vested interest in the power utilities market. It can benefit from a new intense energy technology that integrates well with the existing power grid infrastructure. The space industry can provide the space and transport infrastructure. The civil engineering and mining industries can develop the lunar surface technologies, the energy industry has the distribution network and the grateful public pays for the clean abundant energy The result is far less pollution, saving of fossil fuel which adds up to an active "Mission to save planet Earth".

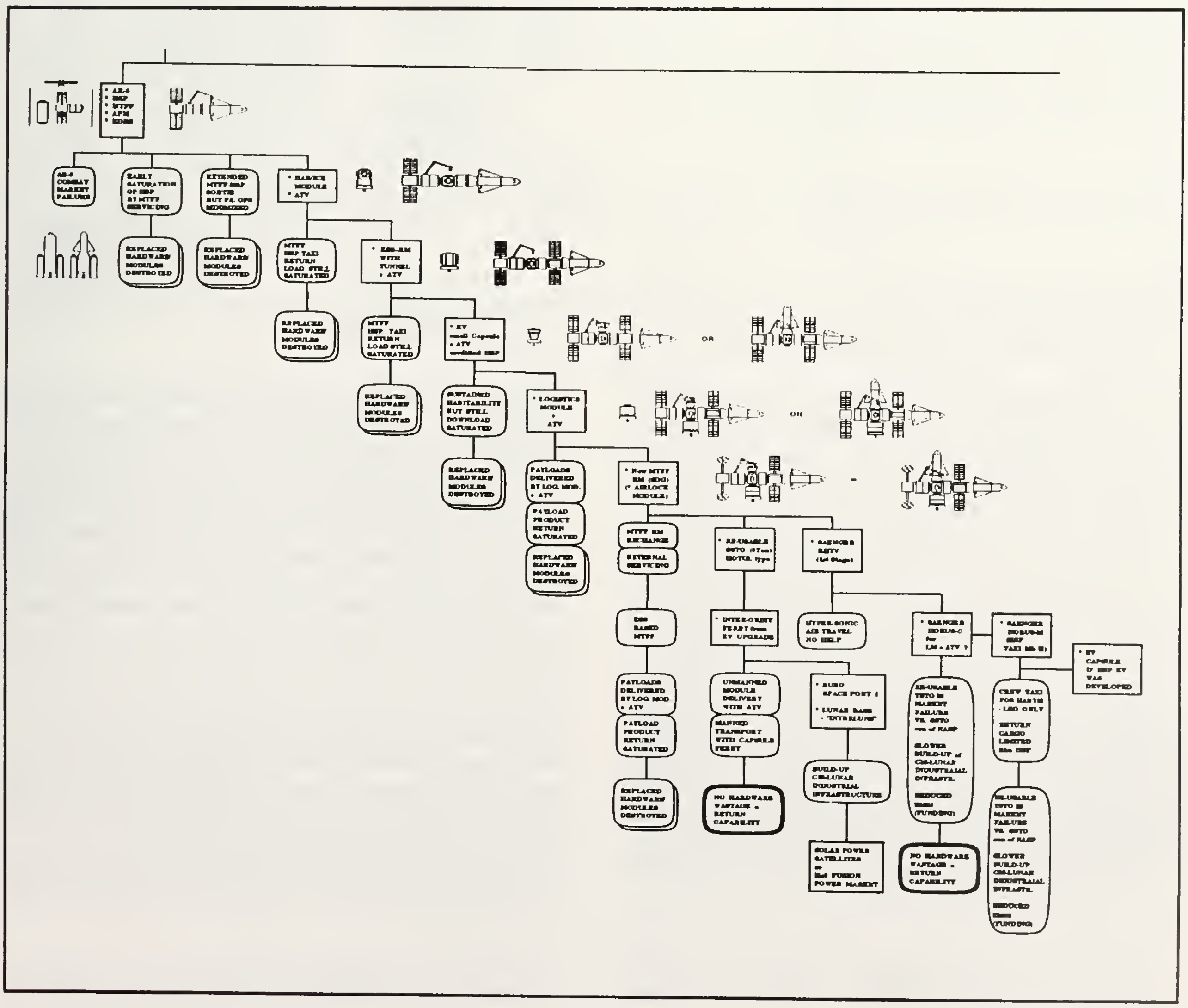
The above scenario is only dimly perceived at present when politicians justify expenditures on space to build some future infrastructure. The space power lobby must increase public awareness of the space option to relieve fear, if adequately funded. The level of funding is a function of fear. Current affairs show that fear of adverse factors generates expenditures to deal with the problem.

The strategic space goal, advocated here, is establishment of a lunar based space power industry for Earth with opportunities in the economic margins, spin-offs and facilities for further research and exploration. This is a major option with Return On Investment potential. It must be assessed by governments.

IMPLEMENTATION PLAN

ESA officials are already on record advocating a new international authority for the proposed Space Exploration

Figure 2 EMSI Strategic Plan Decision Tree Baseline Option



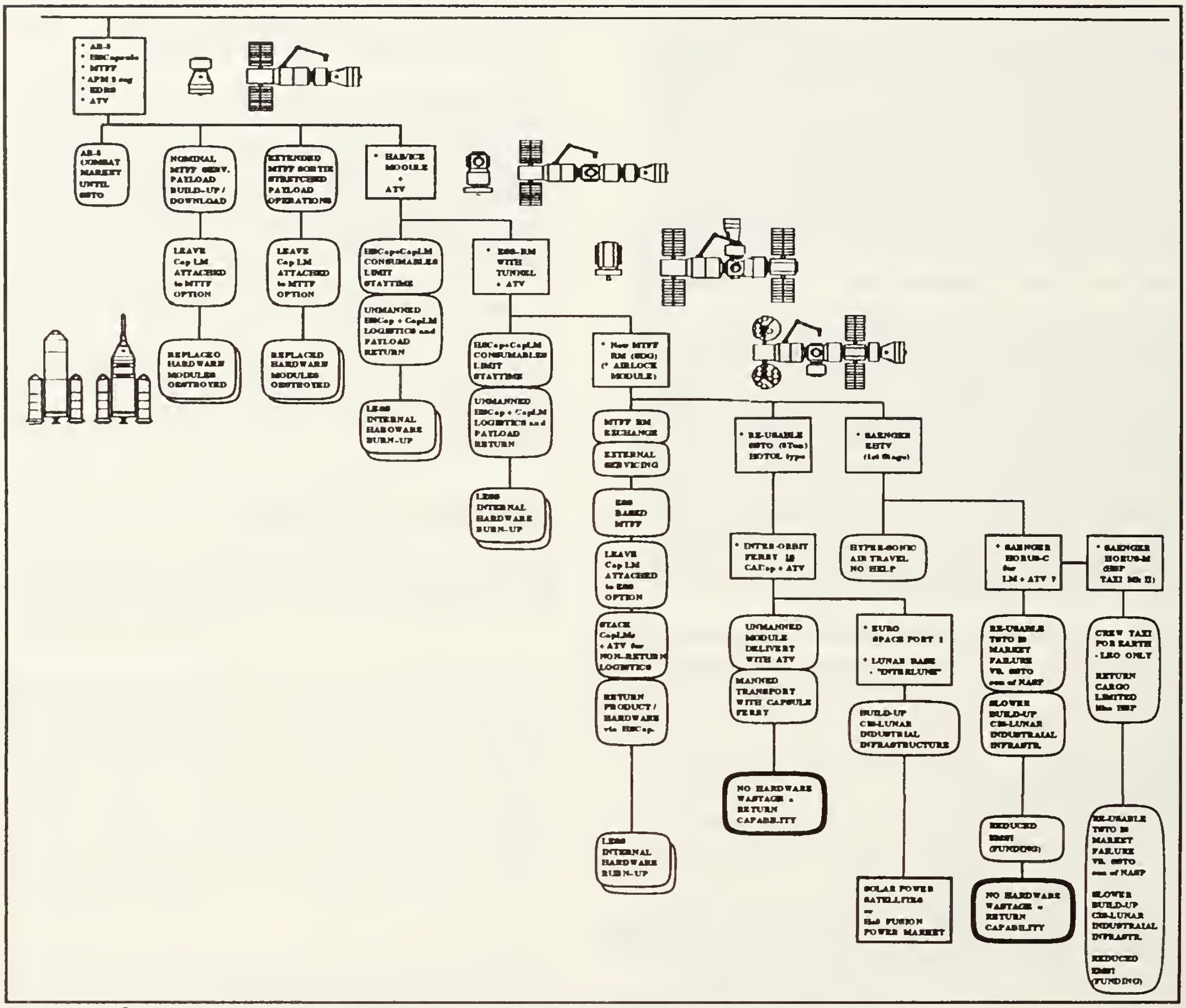


Figure 3 Option with fewer elements to develope, but same function and strategic goal

Initiative modelled on other international space organizations (Intelsat/Inmarsat) as the best institutional structure to implement a space infrastructure after Space Station Freedom. With a lunar based space power goal, such a body could sustain a resilient build-up programme.

Lessons learned about project costs can also be applied to each infrastructure element. A successful project management style is the "skunk works" where a select team implement the design and manufacture of very new aircraft systems at or under the initial price estimate and on schedule. Conventional industrial consortia cannot achieve such successes. Against this ideal solution must be weighed the political pressures to achieve "just retour". The political sector seem disinterested in the inefficiencies, overheads and delays induced. When funding peaks per annum are deemed excessive by the politicians they spend more funds in total by stretching a project's duration. Management techniques can mitigate such distractions but radical solutions will have to be adopted to better control the costs.

As stated above a cost of 1 BAU (2 Billion DM) can be used as a first guess of total development cost for each orbital element. Any Strategic plan that starts with no infrastructure and plots a course to a space industrial infrastructure will have to minimize the number of different elements that need to be developed. The concepts and architecture for Phase 3 of an EMSI or a US/international industrial space infrastructure are only preliminary today and certainly not optimized. Most recent examples of such work are the "90 day study" for NASA and British Aerospace (Stevenage) studies that examine the EMSI without ESA constraints. Even these studies stop after establishment of an initial base and oxygen recovery plant. Such a scenario will require some 20 years to reach routine operations.

The prospects seem bleak if we measure the pace of SSF or Hubble Space Telescope development. It should be remembered that NASA has had to fight very hard for funds ever since the success of Apollo. The pace of the Columbus project is no better because of the political climate and the myopic justifications presented by its supporters.
The political attitude must be changed so that the eventual worth is appreciated as well as the immediate cost amortization.

Taking an optimistic view, the ERNO team offered a graphical summary of the major EMSI architecture options that can still

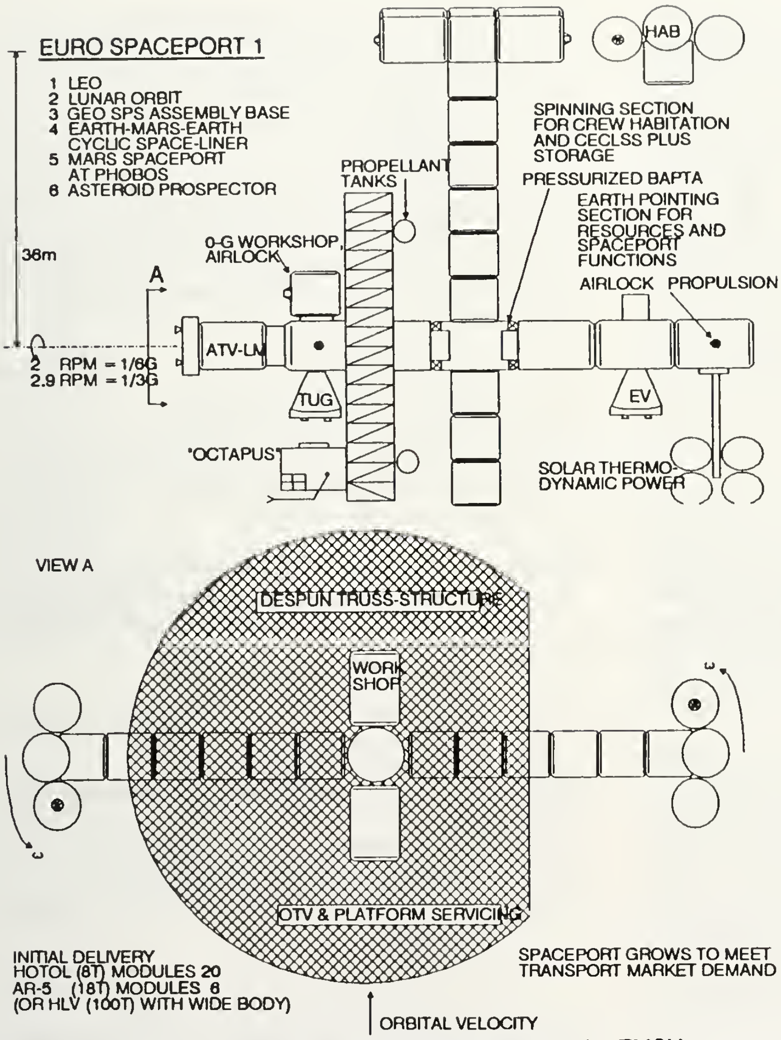


Figure 4 A concept for a commercial product based on the EMSI investment

be considered in ESA's Strategic Planning for the EMSI. The two preferable options that provide the most rapid build-up of capability are presented in figures 2 and 3. British Aerospace has proposed a single module design that combines functions of otherwise different modules for Interconnection, Habitation, Laboratory and Resources. The ERNO concept builds on the Columbus investment.

A Strategic Plan Decision Tree, of which the above figures are extracted, shows each new element, its operational characteristics and its major limitation to the infrastructure. The Phase 2 ESS is detailed but not Phase 3 due to current uncertainty about its architecture. However the most important enabling factor for Phase 3 is shown, radically lower cost ($1000 per Kg) Earth to LEO and return transport. The major competing concepts of one or two advanced stage vehicles are shown since this branch in the decision tree will be absolutely critical to the future rate of build-up. The development cost can be roughly assessed by counting the number of different elements that need to be developed.

The operational costs depend on the launcher used, the crew taxi, the refuelling/resupply, cargo return logistics missions and ground infrastructure. Radical reductions in operational costs are possible when a new low cost transport system comes on-line. Therefore the design details of a Phase 1-2 ESS need not necessarily be guided by the early transport system but by the planned low cost system which will be its replacement. For initial delivery to LEO, a Heavy Lift Launcher is envisaged so that modules can be practically sized and outfitted. Much more frequent logistics traffic will justify a smaller payload capacity reusable transport system.

A European Space Station is regarded as an essential step leading to the Moon. It will be used during the initial phases 1 & 2 to gain the operational experience and establish the necessary hardware and technologies. This is particularly necessary for crew supporting systems. While robotics will be utilized, there is no overconfidence in robotics to perform all operational tasks. When development costs are considered, there is always a role for human intervention in situ.

In phase 3, having attained a "sustained manned presence" capability, the ESS will evolve as:-

- A servicing center for the Columbus Man Tended Free Flier which has returned to its original role as a quiet microgravity laboratory.
- A transfer node for traffic to and from the moon
- A storage base for resources produced on the Moon
- An assembly base for planetary vehicles and large structures(e.g. demonstration SPS and GEO communications platforms etc.)
- Laboratory facilities for evaluating the effects of the space environment

The Phase 3 ESS does not need to retain the initial architecture which seems optimum for anticipated Ariane 5 performance. With a reusable launcher that is able to deliver modules with a mass of 7-8 tons at a tenth of the cost of a 16-20 ton AR5 launch, a very large orbital complex can be assembled with a mix of small mass produced modules and larger special function modules. Total manufacturing cost is minimized by using standard building blocks where-ever possible.

An example of the potential is shown in figure 4. This Space Port has several potential markets as listed. It features a spinning section to provide Lunar or Martian artificial gravity. The assumption is that this is not a research facility and personnel prefer to be conditioned for the environment of their destination. The other main feature is the work platform where transport node functions are executed. Such in-orbit assets will easily provide the traffic demand needed for justification of reusable launchers. This example is clearly an advanced evolution of a more basic Phase 3 ESS. It is assumed that such a facility has minimal interfaces with visiting vehicles so that the problems of interoperability of elements in multi-partner projects is minimized. Other partners are assumed to be responsible for the Lunar ferry/lander and surface facilities.

PHASE 1-2 ESS

The substantial work on initial ESS architectures cannot be adequately presented in this paper. However a consensus was reached by all of the industrial teams supporting the EWD study for ESA. This consensus has been formulated as the top level specification for the initial EMSI and is reproduced below.

1.0 DEFINITION
This specification outlines the top requirements for the initial ESS configuration which will support European autonomous sustained manned presence in space and forms the first major building block of the EMSI programme.

The requirement values and functions outlined in this specification are applicable to the baseline ESS configuration during the preparatory programme. They are not intended to represent the final values as these will be generated within phase A of a development programme.

2.0 ASSUMPTIONS
The EMSI programme will recognize that the Columbus/Hermes/Ariane programmes will develop the technologies/systems/support infrastructure etc. which shall be used to the maximum viable extent.

3.0 SCENARIO
- Transportation means are the keystone for EMSI: The ESS concept generations shall be coherent with the transportation system generations.
- The purpose of the first generation ESS as part of the overall European space infrastructure is to fulfill the directive made at the ministerial meeting in Rome 1985. That is: "to prepare autonomous European facilities for the support of man in space, for the transportation of equipment and crew and for the making use of low Earth orbits".

3.1 FIRST GENERATION ESS CONCEPT:
- That ESS configuration that can be supported by the transportation means identified in para 4.1..
- Operational lifetime 10 years (Maximum)
- ESS shall provide the functions which will enable the support of demonstrations and learning for sustained manned presence in space.
- The ESS shall provide the functions which will enable the support of demonstrations, learning and research on LEO. The missions being chosen amongst:
  — Life Science
  — Technology
  — Micro-gravity
  — Observation

3.2 SECOND GENERATION ESS CONCEPT:
- Takes advantage of advanced transportation means which give substantial reductions in operating costs.
- The ESS shall support first generation functions plus the following:
  — Transportation Node
  — Servicing Center
  — TBD Commercial Activities
- The ESS can be developed in one of two ways:
  1) Direct expansion from the first generation systems
  2) Evolution to new system design optimized to the advanced transportation means

4.0 TRANSPORTATION INFRASTRUCTURE
- The transportation infrastructure shall provide the means to launch and recovery functions enabling the support of:
  — ESS build-up and growth
  — ESS logistics
  — ESS crew transport

4.1 INITIAL TRANSPORTATION:
- ARIANE 5 as defined in "Ariane Users Manual"
- HERMES
  — up to 4 astronauts
  — payload 3 tons up and 1.5 tons down
- Logistics Vehicle (LOVE) ** WITHIN ESS DESIGN AUTHORITY
  — Expendable
  — 5 - 15 tons payload capability
  — pressurized / unpressurized capability
- Escape Vehicle (EV) ** within ESS design Authority)
  — 4 Astronaut capability

4.2 ADVANCED TRANSPORTATION
  — Advanced transportation system shall provide an annual launch/recovery capability greater/superior than in para 4.1
  — Launch costs should be in the order of 1000 US dollars per Kg
  — Rapid reponse capability to ESS demands within 30 days

5.0 OPERATIONS
- The ESS shall be capable of operating in an orbit of
  — Altitude 300-450 KM
  — Inclination 0 - 60 Degrees

6.0 ESS FUNCTIONAL CAPABILITIES
6.1 BASELINE
- Habitation facilities for 4 astronauts
- Internal payload accommodation for 32 single rack (TBC)) equivalents
  — Total power 6 KW (TBC)
  — 400 Kg per double rack (TBC)
- External payload accommodation facilities
  — 2500 KG (TBC)
  — 2 KW (TBC)
- Other functions:

- — Medical facilities (monitor and treatment)
- — EVA
- — External handling system

6.2 GROWTH CAPABILITIES (for second generation)
Section 3.2 outlines two methods of developing the second generation ESS, one of which is direct expansion of the first generation. To retain this as an option the first generation ESS shall have the provisions to extend the habitable volume and to support external structure and payloads. viz:

- The ESS shall be capable of supporting an additional habitation volume for a 6 man crew
- The ESS shall be able to support 100 tons of additional elements

7.0 SAFETY
Means shall be provided for assuring crew return to Earth from any part of the ESS

Means shall be provided for the minimization of orbital and re-entry debris.
8.0 RESILIANCY
The ESS design shall be capable of recovery from any non-catastrophic failure.
9.0 CREW MISSION DURATION

- — 3 to 6 months

CONCLUSIONS

The results of this review has shown the necessity to generate an overall long term strategy to insure coherence of the future European space infrastructure. The primary goal following the establishment of European sustained manned presence in space is the build-up of a space industry which provides clean abundant energy for the users on planet Earth.

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C1.10 The himalayan hydro machine and space transmission power systems: An asian dream of 21st century

M. ADMODDIE, Bombay, India

SUMMARY

The Himalayan Rectangle (HR), an area rising 1500 km North of a base-line between Karachi and Mandalay, contains onc of the world's largest power potential, and has had endemic power shortages in the last 40 years. It has potential for the bad and the good, political, economic, environmental. It lies vulnerable in the power/economic sector between OPEC in the West and APEC in the East.

The potential of the bad is :

Political instability and religious fundamentalism, bankrupt governments, environmental degradation, inefficient power and irrigation systems.

The potential of the good is :

Millions of talented and enterprising people with a social dynamic for growth and change, and large untapped hydro-power resources.

The chief concept, going beyond the technologies of power and water, is :

a) The catchment eco-development strategies with massive afforestation plans;

b) The setting-up plans to strengthen village level institutions to manage local natural assets of biomass and water;

c) The conversion of Earth's greatest single regional hydro-power potential into a sub-continental power system;

d) The export of power and the development of an inter-regional and international power grid by 2030, when both oil and local eco-systems (biomass) would be dangerously depleted;

e) The organisational needs in SAARC, China, international development banks, U.N systems, and national governments to meet the enormous challenge, combining realism in the short term and optimism in the long term.

RESUME

Le Rectangle Himalayen (HR), une zone se trouvant à 1500 km d'une ligne reliant Karachi à Mandalay, dispose de l'une des plus grandes réserves potentielles de puissance du monde, mais a souffert de coupures de courant endémiques ces 40 dernières années. Il dispose de la possibilité du bien et du mal en politique, en économique comme en matière d'environnement. Il demeure vulnérable dans le secteur énergie/économie entre l'OPEC à l'Ouest et l'APEC à l'Est.

Le potentiel en aspects négatifs est :

L'instabilité politique et le fondamentalisme religieux, les banqueroutes, l'aggravation de l'environnement, les systèmes inefficaces de production d'énergie et d'irrigation.

Le potentiel en aspects positifs est :

Des millions de personnes entreprenantes et talentueuses dotées d'un esprit dynamique en vue du développement et du changement, ainsi que d'abondantes réserves d'énergie hydroélectrique non exploitées.

Le projet principal, qui dépasse les technologies d'énergie et d'eau, comprend :

a) des stratégies de captage et d'éco-développement avec plans de reboisage massif;

b) l'établissement de plans pour renforcer les institutions de village pour gérer les ressources naturelles locales de biomasse et d'eau;

c) la conversion du potentiel hydroélectrique régional le plus grand de la Terre en système d'énergie subcontinental;

d) l'exportation d'énergie et le développement d'un réseau de puissance national et international vers 2030, lorsque autant le pétrole que les éco-systèmes locaux (biomasse) devraient s'épuiser dangereusement;

e) les besoins en organisation au SAARC, en Chine, dans les banques internationales pour le développement, les organisations de l'O.N.U. et les gouvernements nationaux pour relever l'énorme défi, en combinant réalisme dans le court terme et optimisme dans le long terme.

As the 20th century escalates us towards its unpredictable end, and the 21st century opens into unknown space, man weighs in his little hands the perplexing potential for the bad with the challenging potential for the good; a test for big minds in human affairs. One of the world's great arenas for such a confrontation of potential lies in what I call The Himalayan Rectangle and South Asia. By the Himalayan Rectangle (HR), I mean a box rising about 1500 km north of a base-line drawn between Karachi and Mandalay. This is the immediate arena of one of the world's most turbulent regions in the future, with nearly a billion poor people (2000 AD) struggling to survive in degrading and turbulent eco-systems in mountains and plains, periodically set alight by sparks of Islamic and Communist fundamentalism from both sides (with reactive Hindu fundamentalism inbetween), torn apart internally by nationalism, subnationalism, caste and tribal factions. In the West we shall see the rising and declining power of OPEC in the next 40 years; in the East the rising power of APEC in the Asian-Pacific region; in the North the still restless problem of Tibet.

The Potential of the bad

1. Post-1995 OPEC power is likely to rise again, with oil prices pushing beyond $ 40 a barrel, with all its regional economic and political consequences. Islamic fundamentalism and volatility is likely to rise on the tide of oil, 1990 to 2020.

2. Both Islamic and Hindu populations will surge with demographic pressures hard to contain, politically and economically. Internal civil strife within countries may spread to cause international conflicts; there are already signs of such conflict in the whole North-West region of the sub-continent from Sindh and Baluchistan to Kasmir and Afghanistan, and in the North-East states of India and Burma, while Tibet is in a state of periodic unrest.

3. Bad governments trying to survive internal and external pressures, becoming ever more bankrupt, are less able to offer their increasing millions either a better life-style or more secure conditions of law and order. Mr J.R.D. Tata recently described the politics of this region as "competitive, fierce and selfish."

4. Micro- and macro-climatic changes (terra infirma, if not incognita) with extensive deforestation, less rainfall, more run-off, more floods and the consequent problems for agriculture, irrigation and food stability. In similar latitudes in North America (30-35°N), it has been estimated that, with the green-house effect, run-off in the dry period between January and June may increase by 12% ; and in October-December (immediate post-Monsoon months for South Asia) by 22 % ; if temperatures rise by just 2°C in the next quarter century [(1)]. There will be less moisture retention in the soil, less water in silted dams, heavier and larger floods, and nearly all hill springs would have dried up.

5. The unsustainability of irrigation systems with 10% to 20% subsidy, 20% to 35% water wastage, extensive salinity and loss of crop lands, together with declining aid for irrigation systems since 1977.

6. The shortfalls in power generation in the Northern and Eastern states of India from 5% to 50% in the first Seven Plans, and transmission and distribution losses varying from 20% to 30%, with mounting financial losses of the State Electricity Boards.

The Potential of the Good

1. Millions of intelligent, talented people in the region awaiting higher opportunities and options, economic, technological and social ; with an unmistakable dynamic to improve their family's living standards.

2. Over 60m.km of hydro power in the Indus-Ganga-Brahmaputra basins, over half of it still untapped with inadequate storage, and with 80% run-off to the seas. The prospect of the storage of 95 m.acre ft. of the Ganga's monsoon flowing through a combination of devices, leaving only 75m. acre ft. to flow down the rivers is an indication of better and cheaper storage capacity in massively forested ranges[(2)]. Similar potential 10m.acre ft. in Siang and Subansiri rivers in Arunachal in the North-East region (Vergese, 1977). There may be potential for underground storage of over 20 Bhakra dams of far less cost.

3. Allowing for increases since 1975, K.L. Rao's estimates of the existing surface storage of the three major river basins indicate the future potential, especially of the Ganga and Brahmaputra.

(1) "From Climate to Flow", John C. Schaake in Clipmate Variability, Climatic Change, and the Planning and Management of U.S. Water Resources. (N.Y. John Riky 1 Sons.)

(2) *"Ganga Water Machine", Rama, Roger Revelle, Lakshminarayana, "Science", 1975.*

Storage Existing and Under Construction in Various Indian Basins (3)

Basin	Storage million Cu.m	% flow in Basin
Indus	14419	34
Ganga	33476	7
Brahmaputra	142	-

4. A decade ago, The Central Electricity Authority (CEA) of the Ministry of Energy, government of India, estimated the hydro-electric potential of India at 76,200 m.kw at 60% load factor, of which the Northern region accounted for 27,800 MW (then only 10,700 MW) ; indicating a combined potential of the Indian Himalayan region alone of 35,300 MW, with only 13,400 MW, just over a third, utilised then (Financial Express 7.4.79).

5. In the '70's Nepal's hydro potential was estimated at 83m.kw in the Karnali, Gondak and Kosi basins (4). Bhutan's has yet to be assessed and publicised. Estimates of the Tibetan side are unknown. There has been some publicity concerning the enormous potential of the 50 mile hair-pin bend of the Brahmaputra between India and China near Pe with a head of 2200 m; capable of generating 37m.kw. constantly. "The major need of such a project is an assured market demand," says Hiroshi Hosi in "Macro-Engineering"(Technology in Society, Pergamon Press, 1990). Every country in and around the Himalaya has been short of power for the last half century. There is need for reliable demand forecasting preceding hydro-power and energy planning, especially in the next 50 years of greater industrialisation and more developed agriculture and the services sector in the Himalayan Rectangle and beyond in the South Asian region, hopefully to be interlocked in a sub-continental power grid.

Parameters of Response of Potentials

In "Macro" (Blond,1990) Frank Davidson has reminded us that in such vast designs, "the problem is less one of technology than of organisation, finance, politics and, above all, public opinion". I would only add one more essential ingredient, a core of vanguard men and women with imagination and faith to carry the torch forward for decades to come, till that public opinion is lit, till political will is fixed by that public opinion, till social organisation, science and finance begin to work. I now deal briefly - within the constraints of the length of this paper - with the broad parameters of the responses to the potential of this 21st century dream, fully mindful that macro designs have macro problems compounded, and that they need time to grow and achieve.

(3) *"India's Water Wealth", K.L.Rao, Orient Longman, 1975.*

(4) *"Hydro-Power Potential of Nepal", Dept. of Electricity, Kathmandu.*

The Heart Concept

Such a concept has to be multi-dimensional, going beyond the technologies of power and water. Brief indications are given below :

a) The development of the most economic water storage and hydro-power systems in the western, central and eastern sectors of the H.R., in a mix of massive afforestation plans (people-based) in catchment development; and not a mix of large not massive (let Pe on the Brahmaputra wait for 21st century technologies), medium and small dams, preceded by catchment eco-development strategies for forestry of all kinds, horticulture, agriculture and animal husbandry, tourism, and light environment-friendly industries.

b) Such plans should grow from bottom to top - not vice versa as has been the case - from subcatchments and village communities. It is now recognised that the crux of the problem is not deforestation, erosion and floods, but the weakening over the last century of village institutional capabilities of managing their local biomass and water resources; by the politics of plunder; by the policies and intervention of colonial and post-colonial regimes, apart from population growth pressures since 1931. Realising its mistake of 1968 in centralising power in forestry policies, Nepal has been leading the way towards decentralisation since 1978, an example yet to be followed in the region. This is a 'sine qua non' for all eco-development and technology plans of the future. The role of the village community is that of the real manager; the role of the state needs to be transformed into that of a sensitive facilitator, and the major mobiliser of resources and technologies.

c) The conversion of Earth's greatest single hydro-power resource into a sub-continental power system, with space satellites in geo-synchronous orbit; micro-waves transmitting power both ways with over 50% efficiency. "The cost of such power transmission would be independent of the distance of the production centre from the utilisation centres," says Arnaldo M. Angelini [(5)]. (See Appendix from Angelini's paper).

d) The export of surplus power would place the countries owning them in the same conditions as oil-producing countries, but this would be an inexhaustible, renewable resource to countries like Nepal, Bhutan and other Himalayan states; the major hope of their eco-development both directly and indirectly by foreign exchange earnings. Angelini makes two notable observations. First, whilst vast sums are being put into telecommunications as a service; "power transmission is both a service and the supply of a good." Second, in terms of economies of production, he says : "there is no doubt that the cost of photovoltaic power (Satellite power system), is over ten times higher than the cost of untapped hydraulic resources, of which quite a few were capable of producing KWH at costs considerably lower than the nuclear source."

[(5)] *"Proposal for a Programme of Study & Research on the Possibility of Intercontinental Power Transmission Through Satellite" - Arnaldo M. Angelini.*

e) The development of an inter-regional and an international power grid extending over the whole of South Asia, China, and possibly to Japan. And all this in the time-frame of a depleting oil age till 2030, and depleting eco-systems in the H.R. itself by then.

Organisational Responses

a) If the concept has first to be nurtured by the vanguard, it needs an Asian/International equivalent of the Club of Rome, which will need to take it up as the moral substitute for war, poverty, and environmental degradation of the heart ot the Asian continent, the home of its past civilisations. As in the EEC, the concept and its vision need to transform the Himalayan/South Asian region from a cock-pit of political conflict and decay into a 21st century eco-developing community; a region of Power & Peace, bound together in hoops of micro-waves, satellites and power grids. It needs to visualise an Asian Power & Water Community like the Iron and Steel Community in Europe in the '50's and '60's. Where are its Jean Monnets? Perhaps in a mix of statesmen beyond the politics of today, technologists of vision and dedication, journalists of integrity and eminence, businessmen of the calibre of J.R.D. Tata; all presided over in Asia's old 'ouvre' by the benign personality of the Dalai Lama, and/or the practical international visionary, the Aga Khan.

b) When this Asian Club of Rome has carried the idea forward to capture the imagination of men, then to seek the political blessings from SAARC and China, from the Asian Development Bank and Japan, from the World Bank and the Western powers, the international specialist bridges, as suggested by Angelini for his project, may be :

-The U.N and its Commission for Large Power Systems
-The World Energy Conference
-The International Conference on Large High Voltage Electric Systems.

That will be the first step towards international statesmanship.

c) Next, in keeping with the Age of Gorbachov, the substantial demilitarisation of political frontiers in the region, flowing from which a Peace & Power dividend of 0.5 % of the defense expenditure of India, Pakistan and China, at least Rs. 250 cr. or $125 m. a year with contributions from international financial institutions, to begin a 10-year programme of institution building, of catchment development, of Research and Study of the major technological, economic and social problems applied to the Potentials for Good and to the Heart Concept. Such studies should include the geological (seismic),and reliable erosion rates and sedimentation loads in rivers. It may be entrusted to the preliminary international committee set up after c) & b) above, on the lines of the international crop research institutes.

d) In the light of the lessons of the last century, the debureaucratisation and decentralisation of control of Himalayan land, forestry & water resources, and the placing of responsibilities for their management back to the village communities, with the catalytic help of voluntary NGO's. A basic task of the next 10 to 20 years, without which all else will be fruitless.

e) Post-1995 pilot projects in the most potential and productive areas of supply and demand of power & water may be initiated. Marketing should be introduced, as far as possible, in cost-benefit analysis, in loans which are serviced in realistic pricing policies, in taxation of inefficient uses of water and power, and in technical collaboration where necessary.

Any such grand design will inevitably have a variety of problems of Himalayan dimensions. It is only a question of man's imagination, drive, and capability to match them with the enormous and yet unknown technologies of the next century, and when those exciting technologies hopefully lever us out of obsolete mind-sets of earlier centuries. There are some dreams worth dreaming, and this is one of them. It would have pleased Buckminister Fuller, the da Vinci of the age, whose advice to me once was, "Think Big." To which, in the welter of multiple problems, one may add, "Combine realism in the short-term with optimism in the long-term."

FIG. 1 - WORLD HYDRO POTENTIAL BROKEN DOWN BY LARGE AREAS

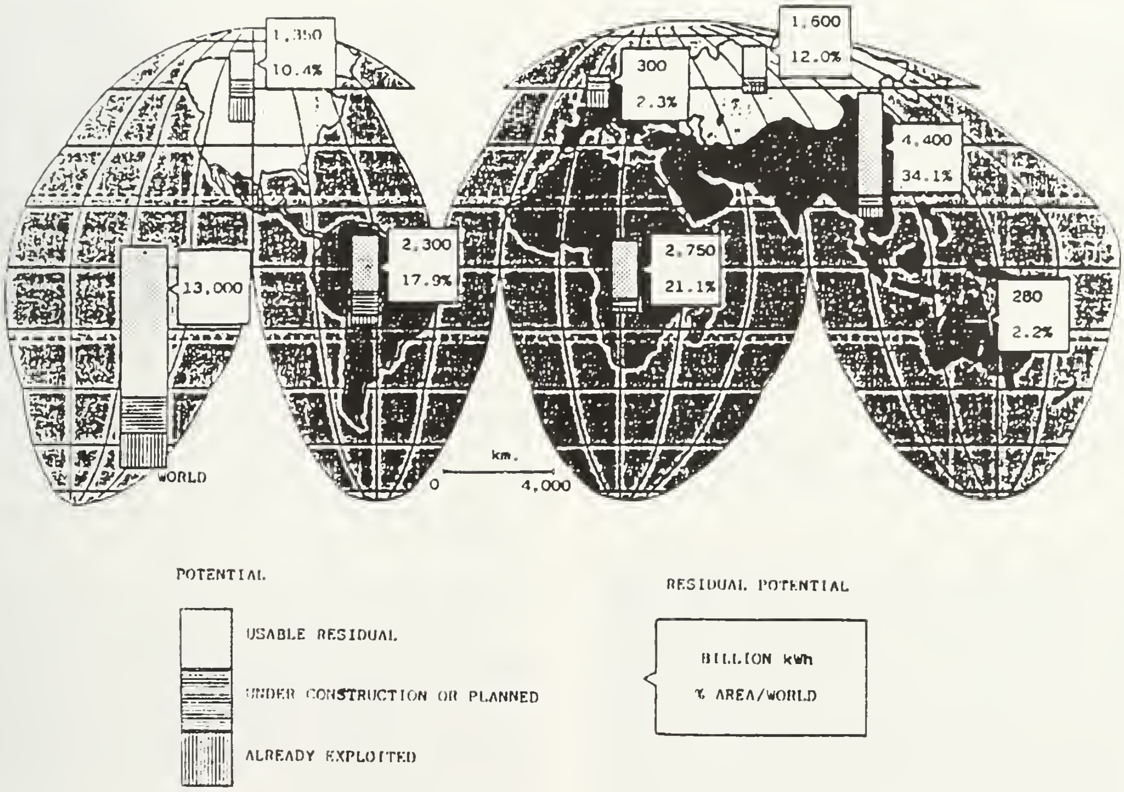
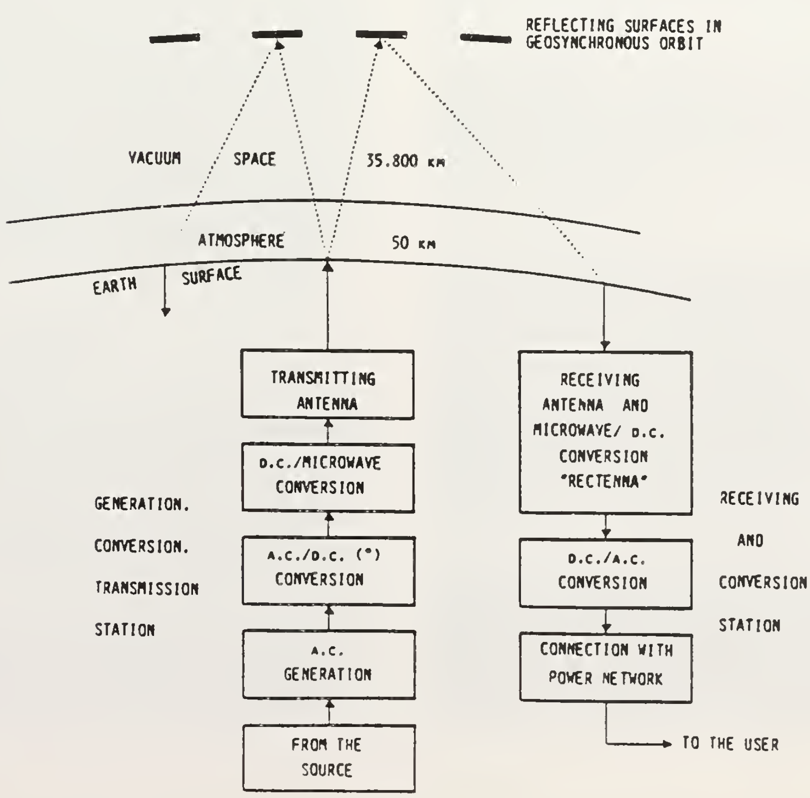
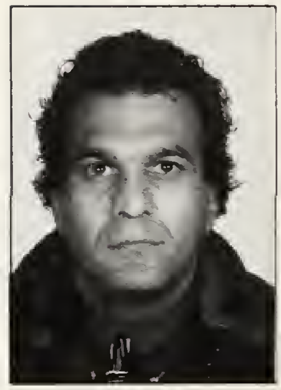


FIG. 2 - SYSTEM CONCEPT OF THE SATELLITE ELECTRIC POWER TRANSMISSION SYSTEM (S.T.S.)



C1.11 Project Phoenix. Fire Replaced: Solar Power and Global Warming

C. OWEN, H. KAVINSKY - Illinois Institute of Technology, Chicago, USA



Résumé

Le projet "Phoenix" est une proposition de design portant sur un ensemble de projets destinés à combattre le réchauffement général de la planète. Le rapport décrit l'un d'entre eux : un projet de satellites à énergie solaire destinés à réduire notre dépendance en énergie fossile. Dans cette proposition, la Lune est la principale source de matériaux structuraux et fonctionnels. De grands, 10 Gigawatts, satellites en double-cône de 9,25 kilomètres de diamètre sont construits en orbite lunaire et remorqués jusqu'à une orbite géostationnaire. Le nombre de ces satellites requis pour enrayer efficacement le processus de réchauffement planétaire nous suggère la mise en oeuvre de projets pilotes dès aujourd'hui, et une révision des plans de la future station spatiale et du développement lunaire à long terme.

Abstract

Phoject Phoenix is a design proposal for a combination of projects to combat global warming. In this paper, one of these is explained -- a plan for solar power satellites to reduce dependence on fossil fuels. In the plan, the Moon is the prime source of functional and structural materials. Large, 10-gigawatt, double-cone satellites 9.25 kilometers in diameter are constructed in lunar orbit and towed to geosynchronous orbit. The number of such satellites required to contribute to a global warming strategy suggest pilot projects now and a review of plans for both the forthcoming space station and follow-on lunar development.

Introduction

The Design Team

Ruby Dosen, Jerome Llerandi (*Team Leader*), Howard Kavinsky, Mahmoud M. Nagib, Marzena Sleczek, David J. Zabloudil and Charles L. Owen (*Adviser*).

The Problem

While a number of sources contribute to the so-called "greenhouse" gases causing global warm-up, the unbalancing source has been created by man. Two gases, carbon dioxide and methane, are the primary culprits. Both are produced as byproducts of many of the industrial, commercial and even individual activities of human society.

The *Greenhouse Effect* is caused by the absorptive characteristics of the greenhouse gases as they react to radiant energy. While they are transparent to radiant energy in the visible spectrum (and, therefore, pass sunlight through to the Earth), they absorb radiant energy in the infrared range of the spectrum. Heat generated on Earth that would otherwise radiate away to outer space is trapped and re-radiated back to Earth by the greenhouse gases. In normal proportions, there is a balance among the gases of the Earth's atmosphere that maintains temperatures and climate in the familiar life-supporting patterns we know. Although they compose less than 1 per cent of the Earth's atmosphere by volume, the greenhouse gases are a vital factor in this life support system.

Of the greenhouse gases, carbon dioxide is the gas of most concern. While methane is 20 times more effective than carbon dioxide in trapping heat, its concentration in the atmosphere is less than one one-hundredth that of carbon dioxide. Other greenhouse gases, nitrous oxide and -- particularly -- the chlorofluorocarbons (Freon is a commercial example) are very potent, but less influential because of their lower concentrations in the atmosphere. Their increasing presence is worrisome, however, for other reasons -- acid rain and the destruction of the ozone layer.

In a normal year, many billions of metric tons of carbon are removed from the atmosphere by the natural processes of photosynthesis and the physico-chemical diffusion of carbon dioxide into the seas. The Earth, in turn, returns back to the atmosphere approximately the same number of billions of metric tons of carbon in the form of carbon dioxide through processes of soil and plant respiration and physico-chemical diffusion from the seas. Over the last two centuries, man has upset the balance. Scientific estimates now place the number of metric tons of carbon removed from the atmosphere annually by natural processes at approximately 204 billion. Added to the atmosphere are approximately 207 billion metric tons of carbon, of which 5 billion tons are produced by burning fossil fuels and 2 billion tons are released by deforestation. The *net gain* of *3 billion metric tons of carbon per year* is the primary cause of global warming.

The Project

The Greenhouse Effect, was the topic for investigation by teams of fourth year and graduate students in the Institute of Design's ***Systems and Systematic Design*** class in the fall of 1988. Work began in 1988, continued independently into 1989, and on through 1990 in the development of a computer-produced presentation of the concepts. Using a computer-supported design process called Structured Planning to gather and organize information from a large number of sources, the teams devised two proposals to confront the global warming problem.

Both proposals grow out of reflection upon a basic greenhouse equation: carbon plus oxygen produces carbon dioxide -- the chemical representation of the common phenomenon of fire. The first approach (the subject of this paper) takes the equation as is and asks what can be done to contain its effect. In this

approach, the effort is toward reducing the amount of CO_2 in the air by reducing the amount of carbon burned -- in essence, replacing fossil fuels as a source of energy. The second approach reverses the equation and asks what can be done to remove existing CO_2 from the air. This approach leads to means for augmenting photosynthetic processes and is covered separately in another report.

Over the course of the year's work the ***Project Phoenix*** design team developed proposals from a number of concepts created to blend the best ideas discovered in the process of information gathering with new ideas invented to fulfill un-met needs. The results, should be treated as *a conceptual plan* -- really *a problem statement* for projects to be carried on at a more detailed level. The ***Systems and Systematic Design*** class is charged with teaching the Structured Planning process for converting data to information to concepts. Projects conducted in the class characteristically produce ideas that exhibit complex interactions and mutual goal-supporting behavior. The objective is to deal with information-intensive problems at a high enough conceptual level that solutions can be postulated and tested against a wide range of contextual information before detailed solutions are attempted. In this case, final concepts were visualized with drawings and models, and (for the first time) computer-generated renderings. The renderings included as figures in this paper are computer-generated.

One of the things that a university can and should do is involve itself in projects that have social value. Although these (desirably) could have commercial value, they may be too risky or of too uncertain value for industry to undertake. ***Project Phoenix*** is such a project. Like many previous projects undertaken at the Institute of Design, it confronts important problems not yet being adequately addressed by others. For ***Project Phoenix,*** the design teams volunteered nearly 10,000 man-hours of time, only a small part of it required for the purposes of the class. We hope that the results of their work will motivate others also to timely efforts on the global warming problem -- before it is too late.

Space-Based Power

Environmentalists for years have called for the use of natural energy sources to replace fossil fuels. Wind, sun, rivers, waves, tides and geothermal sources have all been harnessed locally where they are effective. Independently or in conjunction with conventional fossil fuel energy sources, they reduce dependence on fossil fuels -- which, in any event, have a limited life expectancy (the supply of fossil fuels will probably fail to meet global requirements by 2050). Although controversial, a potentially major replacement energy source is nuclear power. If nuclear fusion becomes practical, it will present a comparatively clean alternative to the fission reactors now used. As the situation stands now, fission reactors are no longer regarded as attractive power sources.

Excepting nuclear fusion, none of these alternative energy sources, as they now are conceived, offers a large enough contribution to offset the enormous need for energy now existing and projected for the future. Contemporary developments in nuclear fusion have been unable to produce energy at rates greater than the energy required to sustain a reaction. While it would seem certain that fusion research must eventually produce successful results, it is not clear how long it will take to be able to meet needs on the scale confronting us now. Even combinations of the various alternative energy systems are not promising for the truly large scale replacement required.

Energy use by North Americans alone is now over 300 gigajoules (GJ) per capita per year. 1985 estimates placed total world energy use at approximately 319 exajoules (EJ). A gigajoule is 1,000,000,000 joules; an exajoule is 1,000,000,000,000,000,000 joules. In somewhat more familiar terms, one EJ is equivalent to 200,800,000 MWhr (megawatt-hours) of electricity or the energy produced from 22,340,000 metric tons of oil. That amount of oil would require 49 of the world's largest oil tankers, the ultra large crude carriers that cannot enter conventional ports and take almost five kilometers to stop. Estimates of future energy demands place annual world needs at 800 to 1000 EJ by 2030.

Excepting energy created from nuclear fission or fusion, the Earth receives its energy from the sun. Whether locked up in fossil fuels or temporarily transformed in wind, wave, heat or other energy form, it originally arrived as radiant energy from the sun. Considering the losses in energy that always take place as one form is changed to another, it is most efficient to extract it for human use as it arrives -- in sunlight. A prodigious amount of energy falls on the Earth as sunlight -- about 5,600,000 EJ per year. At the distance of the Earth's orbit, a single square meter of surface facing the sun receives 1,372 watts of energy.

Over the years, attempts to use the sun's energy to power man's works have been limited to small scale projects because of low energy conversion efficiencies. Recently, however, research in photovoltaic energy conversion, the direct conversion of light to electricity by solar cells, has yielded efficiencies of as much as 30 per cent. As production costs are driven down, photovoltaic power should now become practical for many applications.

In spite of this success, two considerable difficulties face any plans for large scale development of solar energy generation systems. The first is the large commitment of Earth surface required for solar collectors. The second is the intermittent availability of sunlight, diurnally masked by the Earth itself, and unpredictably interrupted by weather systems.

A solution to these problems is the transfer of the power generation system to outer space. First proposed in 1968 by Peter Glaser in the journal ***Science,*** such a system could take maximum advantage of solar radiation. Sunlight converted to electrical energy by photovoltaic solar cells could be beamed to Earth on tightly directed microwaves. Stationed in geosynchronous orbit 35,800 kilometers above the Earth, Solar Power Satellites could be as large as conveniently practicable and would not be affected by either the intermittent sunlight problems of Earth surface conditions or the ravages of atmospheric erosion and corrosion. On Earth, the power received would be clean electrical power distributed through the international power grid, or available for the hydrolysis of water into hydrogen -- another clean source of power that can be used for remote, portable or mobile applications where it is awkward to use electrical power.

The design problem is how to construct large scale satellites in space. Even with reduced requirements for structure and protection made possible by deployment in space, great amounts of material must be amassed for each satellite -- amounts beyond the logistical capacity of chemical-based rocket systems. Lifting such large masses from Earth to orbit is a forbidding and costly task -- twelve times the cost of moving the same mass of materials from the moon to geosynchronous Earth orbit. There are other advantages to working in space. The construction of large, pure crystals of silicon for photovoltaic cells can be done with relative ease in a micro or zero gravity environment. Construction in space also benefits from lack of gravity -- structures need only maintain form and resist inertial forces. Low-mass, omni-directional, tension/compression structures can replace the kinds of materials-intensive, weight-supporting structures used on Earth.

Space Station Rethought

Over the past twenty years, planners in the United States and the Soviet Union have devoted considerable discussion time to the sequence of events to be followed in the next phases of manned space exploration. A particular point of contention in the discussions has been the value of a space station and its potential role as an Earth-oriented experimental/commercial laboratory, a way station for moon colonization or a staging base for voyages to Mars and beyond. ***Project Phoenix*** projects a role for a space station most similar to the latter two roles, in which it serves as a transfer station between Earth to Low-Earth-Orbit (LEO) operations and LEO-to-moon operations.

Gravity-imposed costs of lifting materials from Earth to LEO require a reusable vehicle such as the space shuttles now used by NASA and soon to be deployed by the USSR. Future versions of this vehicle may be hypersonic "aircraft" able to fly to LEO, but they will continue to be specialized vehicles adapted to high-gravity/low-gravity operations. For travel between LEO, lunar orbit and geosynchronous orbit (where the Solar Power Satellites will be positioned), another type of space ship will be more effi-

cient -- a lunar shuttle. Transfer between Earth shuttles and lunar shuttles will be best conducted at a space station in LEO.

Fig. 1
Hypersonic shuttle craft ferry cargo from Earth to space stations in low Earth orbit.

During the years that the array of Solar Power Satellites is being constructed, there will be constant movement of astronauts and equipment between Earth and construction sites in space and on the moon. A space station to serve this traffic should have a permanent crew and facilities to handle docking and cargo transfer for more than one space ship at a time.

Fig. 2
Space stations in Earth orbit are marshaling yards for Earth traffic to Moon Base and the Solar Power Satellites.

The space station for ***Project Phoenix*** maintains crew quarters and support facilities at Earth gravity by locating them in a ring and rotating them at a velocity sufficient to simulate gravity by centrifugal force. Other portions of the space station remain stationary with respect to the station's orbit around the Earth, with the exception of the solar cell power array, which tracks the sun when it is in view. Personnel transfer tubes connect support and habitation facilities to the central axis of the station, and transfer tubes radiating from the central axis complete crew members' access to the docking area. Docking positions are on the perimeter of a large, square space frame that serves as both warehousing and mooring space. Incoming Earth shuttles dock along the outer sides of this space frame and transfer cargo to its inner sides. Lunar shuttles subsequently dock at the same locations and reload the cargoes for delivery to Moon Base, the Lunar Orbit Factory or a Solar Power Satellite.

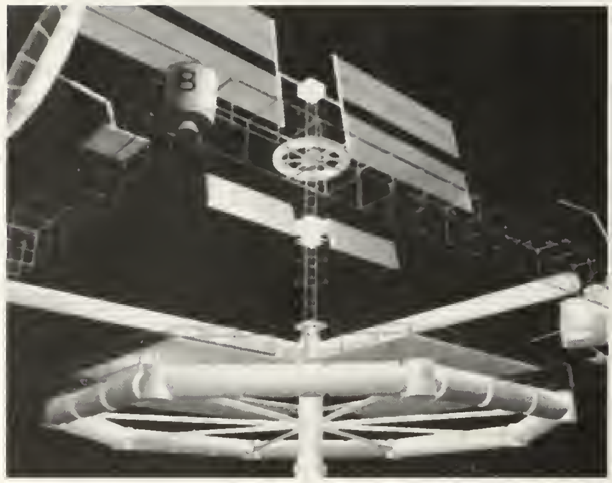


Fig. 3
A rotating ring of habitats and work stations below the docking frame maintains an environment of artificial gravity for permanent and transitting workers.

Fig. 4
Piers for shuttle craft from Earth and trans-lunar shuttles occupy four sides of the docking frame.

Moon Base

For ***Project Phoenix,*** the moon is the source of raw materials needed to build the Solar Power Satellites. Available on the surface are virtually unlimited supplies of silicon and aluminum in the form of silica (silicon dioxide) and alumina (aluminum oxide). Silicon, in pure crystal form, is the material necessary for the photovoltaic solar cells; aluminum is a good electrical conductor and, alloyed for strength, is an excellent structural material.

Silica, alumina and other ores are widely deposited on the lunar surface as dust and small particles. Silica represents approximately 46 per cent of the lunar rock found in both maria and highland sections of the moon; alumina varies from 13.9 per cent of the rock found in the maria sections to 23.4 per cent of the rock found in the highland sections. Surface mining techniques

similar to strip mining on Earth can be used to collect ores for processing. Once collected and subdivided mechanically (if not already in particulate form), they may be processed by magnetic and electrostatic techniques to separate undesirable ores from those high in alumina and silica.

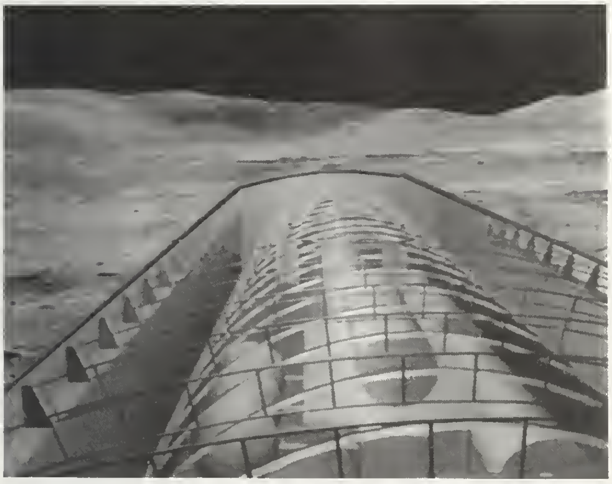


Fig. 5
A base on the Moon mines minerals and processes them into the raw materials needed to build structural members and solar cells for Solar Power Satellites.

Several processes for smelting ores have been studied for their suitability on the moon. One such process that appears to be feasible would be similar to that used by for electrolysis of aluminum from aluminum chloride in molten chloroaluminate melts. The ores would be combined with an electrolyte of cryolite (Na_3AlF_6) and fed into bipolar electrical cells. Powered by an SMES (Superconducting Magnetic Energy Storage) supplied by solar energy, these cells would electrolyze the aluminum oxide, silicon dioxide, ferrous oxide and titanium dioxide content of the ore, forming oxygen at the anodes and an aluminum, silicon, iron and titanium alloy at the cathodes. The two products, separated by the weak lunar gravity, would be removed continuously from the top and bottom of the cells. Periodically, when the oxides are exhausted, calcium and magnesium compounds accumulating in the electrolyte would be removed by additional electrolysis at higher voltages. The remaining cryolite would be recirculated as the electrolyte for continuing operations. The near vacuum on the Lunar surface, absence of oxidizing gases and widely differing vapor pressures of the four elements in the alloy product make it feasible to separate the elements by fractional distillation.

Aluminum and silicon in purified form, along with oxygen and other products, are shipped from the moon to lunar orbit by means of a mass driver. Because the moon's gravity is weak (one sixth that of the Earth), it is practical to literally fire containers and blocks of material as projectiles into lunar orbit. The mass driver operates on the principle of the linear induction motor, providing constant acceleration to a projectile by electromagnetic induction. Super conducting magnets in a "truck" that travels on the mass driver track suspend the truck and its payload above the track without friction. Magnets in the track, turned on in sequence as the truck passes over them, impart the acceleration needed to bring the truck and its payload to escape velocity for the moon -- 2400 meters per second. When escape velocity has been reached, the truck slows, continuing to follow the moon's surface curvature on the track, while the payload continues outward to lunar orbit. Freed of its payload, the truck circles back on the track for another load, returning energy to the system as it is braked electromagnetically.

Lunar Orbit Factory

The Factory for producing components for the Solar Power Satellites is located in lunar orbit where it can receive raw materials from Moon Base and take advantage of micro-gravity conditions to process them. By carefully maintaining orbit in relation to the mass driver's orientation, it is possible to position the Lunar Orbit Factory so that the trajectory of projectiles is nearby and the relative speed of approaching projectiles is low.

A mass "catcher" snags the projectiles of silicon, aluminum and other materials as they approach the Factory. Stretched within an opening approximately one square kilometer in area, is a target held by cables on reels on an oval track. The cables can be reeled in and out to enable the target to move into the path of a projectile and to move with it as it makes impact. Incoming projectiles from the mass driver are located by radar far enough from the mass catcher that the target can be positioned to center the catch. When a projectile is caught, projectile, target and reels roll around the mass catcher's track, slowing the projectile to a speed only slightly faster than that of the orbiting Factory. At the end of the track, the target and reel system speed up and circle around to return to the front for another catch. The projectile, free of the mass catching system, continues into the Factory's storage area.

Fig. 6
A Lunar Orbit Factory circling the Moon makes solar cells and Satellite structural members from Moon-mined raw materials.

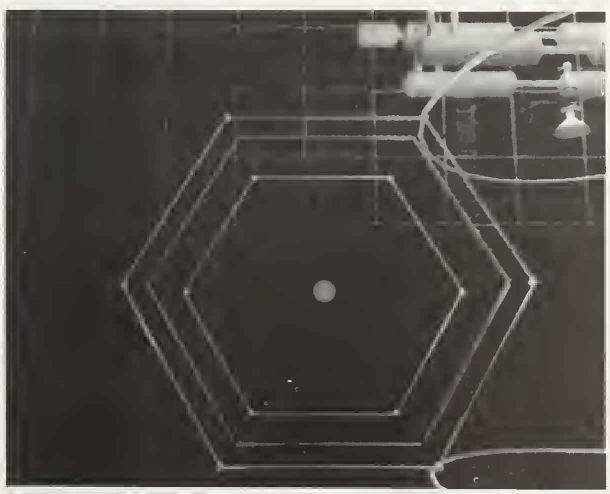


Fig. 7
Raw material capsules fired from the mass driver on the Moon are captured by a Mass Catcher. A target within the one square kilometer entry ring moves under radar control to meet an incoming projectile.

Processing of aluminum at the Factory consists of alloying it with strengthening metals, extruding it into structural shapes and forming beams and other structural members with the basic elements. A solar furnace provides the heat necessary to melt and alloy the aluminum. Extruders process the alloy into strip form and pass it to automated beam builders that "extrude" finished beams. A beam's continuous longitudinal members are held in proper relationship by cross members welded in place at regular intervals and strengthened by diagonal tension braces. The completed, welded beams are low in mass and strong over long lengths.

Solar cells are made in the Lunar Orbit Factory from large silicon crystals grown in micro-gravity. Enclosed in glass sandwiches for protection and mounted on large panels interconnected with aluminum power buses, they are produced by manufacturing and assembly robots and stored externally for final assembly into Solar Power Satellites.

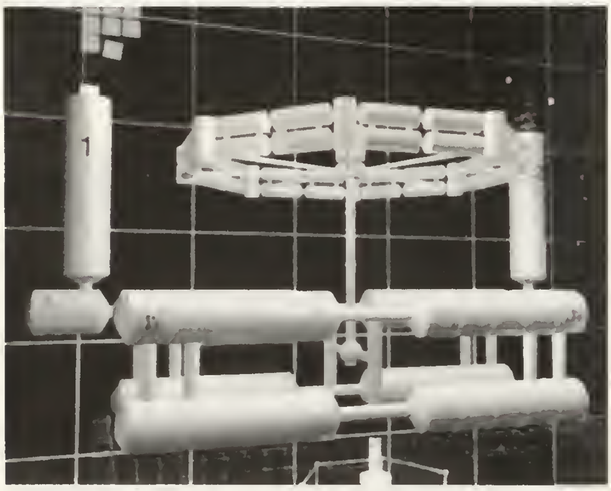


Fig. 8
The Lunar Orbit Factory produces alloys, builds trusses and other structures from aluminum and titanium, and grows silicon crystals for photovoltaic solar cells.

In the immediate vicinity of the Lunar Orbit Factory, robots construct satellites in basic form from the solar panels and beams. Major onboard structures, such as the SMES (Superconductive Magnetic Energy Storage) and transmission antennas, are also assembled as completely as possible and mounted. When a satellite has been completed to this stage, it is towed by lunar shuttle to its operating position in geosynchronous orbit. Here it is outfitted with the remaining special equipment brought up from Earth, and placed in commission.

Solar Power Satellite

Assuming a 30 per cent efficiency factor for photovoltaic energy conversion and a conservative 60 per cent transmission efficiency, it would take 116 billion (plus or minus 13 billion) square meters of solar panels to supply all the energy necessary for the world of 2030. One thousand Solar Power Satellites of 116 square kilometers surface area each would furnish this power.

It may not be necessary, however, to put such a massive solar power system into space to combat the Greenhouse Effect. The Earth, as it is, is capable of absorbing two fifths of the carbon produced by mankind's present energy load (eliminating 3 billion of the 5 billion metric tons of carbon produced would bring the carbon dioxide production/absorption system into balance). In 1985, fossil fuels provided 90 per cent of the world's energy. Assuming that little has changed since then, the five billion tons of carbon represent about 330 EJ. Two fifths of that, 130 EJ, can still be absorbed by a balanced system. Further, a major effort to remove greenhouse gases from the atmosphere will extend the margin; it is reasonable to think that an additional 2 billion tons of carbon might be removed by a successful program of re-greening, allowing another 130 EJ to be produced by carbon fuels. Finally, the portion of the total energy obtained from non-fossil fuel sources (nuclear, hydroelectric, geothermal and other sources) can be expected to at least expand at a constant rate -- remaining 10 per cent of the growing energy supply. Thus, the energy necessary from space can be reduced by 130 + 130 + 90 EJ, or 350 EJ. The result, 550 EJ (a middle estimate of 900 EJ for what will be needed, minus the 350 EJ), may still be conservative on the high end if nuclear fusion becomes available, alternative energy sources are more actively developed on Earth, or efforts to restore the natural environment are optimistically successful.

For a requirement of 550 EJ per year in the year 2030, 70,621 square kilometers of solar panels will be necessary, assuming 30 per cent efficiency for solar power conversion and 60 per cent efficiency for transmission to Earth. A number of studies have recommended power generation, at least initially, in the range of 5 to 20 gigawatts (GW) per satellite. For a satellite generating 10 GW in space, 23 square kilometers of solar panels will be needed. Allowing for losses in transmission, 3,065 such satellites will produce the required 550 EJ; each will produce nearly .2 EJ per year. Early experience with satellite construction and operation may revise decisions on size -- in that case, fewer numbers of more powerful satellites may be constructed.

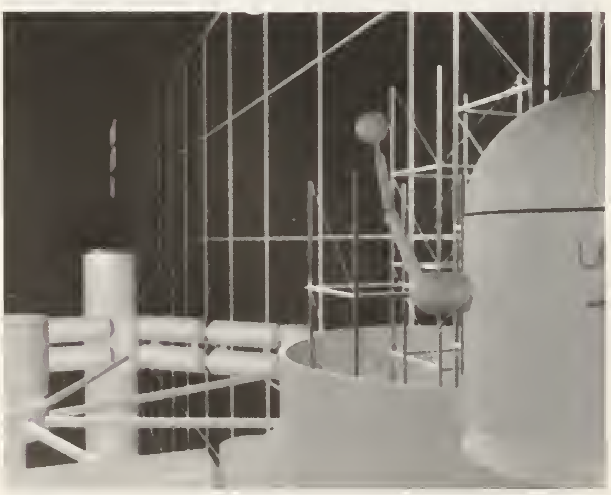


Fig. 9
Solar cell panels and structural elements are assembled into Solar Power Satellites in the vicinity of the Lunar Orbit Factory.

Fig. 10
Large panels, 1200 meters on a side, are assembled from medium panels. Tension/compression geometries enable enormous structures to be built.

Fig. 11
A Solar Power Satellite over nine kilometers in diameter spins on its axis to maintain axial orientation toward the sun, while transmission antennas on its central arm track receiving stations on Earth.

A Solar Power Satellite (SPS) is constructed as a double cone with an axis 3.75 kilometers long, and with circular bases 9.25 kilometers and 6.75 kilometers in diameter. Eight large solar panel arrays are connected in a ring at the base of each cone. Each of the large panels is made up in turn of four medium-sized panels, individually constructed as tension/compression structures with central masts and cable systems. These medium-sized panels, 745 meters square, each are made up of four "small" 372 meter square panels containing 90,000 square meters of silicon solar cells each. Aluminum buses connect cells, small panels, medium panels and large panels, and transmit current along structural beams from the rings to the center of the double cone. There, power control equipment and an SMES, capable of storing 5 GW of power, manage the production and transmission of the energy to Earth.

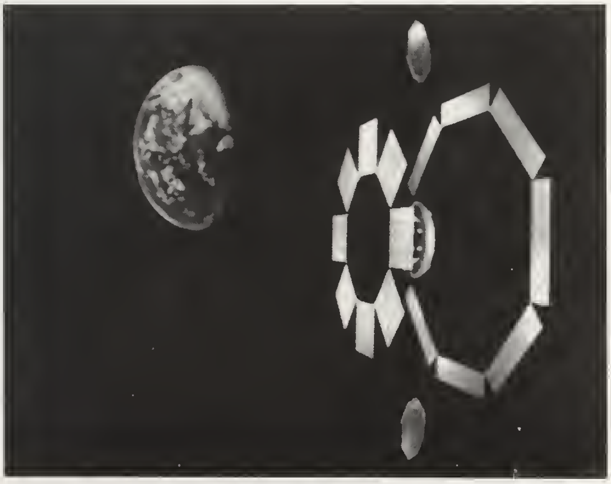


Fig. 12
Solar Power Satellites in geosynchronous Earth orbit provide ten gigawatts of continuous power unaffected by weather or the Earth's diurnal cycle.

The double cone system maintains its axial alignment toward the sun by spinning on its axis. The spinning cone design also reduces material and structural requirements by enabling more use to be made of tension/compression mechanics. For transmission, an SPS has two large panels (1 square kilometer each) of klystron radio frequency amplifiers integrated with antenna elements. Mounted on opposite ends of a beam projecting outward in both directions from the double cone center, these panels extend beyond the envelope of the spinning solar panels to a distance of 5.9 kilometers from the axis. The transmission panels independently track receiving Rectennas on the Earth's surface. Attitude control for them is provided by argon ion thrusters. Power is transmitted as a Gaussian microwave beam at a frequency of 2.45 gigahertz (GHz)

Rectenna

Rectennas for power reception are located in remote areas on land and sea. In shape, they are elliptical with the major axis perpendicular to the equator to conform to the intersection of the Earth's surface with the conical beam projected from an SPS. The ratio of the major to minor axes of the ellipse varies with the latitude where the Rectenna is placed; longer major axes are required for Rectennas at higher latitudes. Because all Solar Power Satellites must be over the equator for geosynchronous orbit, Rectennas are limited to latitudes at which their major axes will not be too long. A Rectenna at 34 degrees latitude (the latitude of Los Angeles), for example, would be 10 kilometers by 13 kilometers in size.

Fig. 13
Elliptical Rectennas (10 by 13 kilometers at 34 degrees latitude) receive microwave energy beamed from space to locations on land and sea.

The receiving surface of a Rectenna is made up of rows of parabolic reflector/collectors parallel to the minor axis. The reflector/collector units, 25 meters long by 3 meters high, encase metal reflector wires less than 10 centimeters apart (the wavelength of the microwaves) in an extrusion that is transparent to microwaves. The encasement protects the wires from atmospheric forces (desert or ocean corrosion) and is easily cleaned by a tracked automatic cleaning machine. Parabolically concentrated waves are reflected to a collector strip in the back of the adjacent unit. 65,000 reflector/collector units are required for a single Rectenna.

Orientation and permanent positioning are important for a Rectenna, but absolute flatness is not. As long as the reflector/collector units are relatively perpendicular to the axis of the beam, they will function as designed. This means that installations in desert areas can be made without undue regard for flatness, and installations at sea can take the motions of waves -- even storms -- without losing efficiency. For installation at sea, a Rectenna is mounted on SWATH (Small Waterplane Area, Twin Hull) flotation supports. These place the supporting flotation body well below the water surface and the supported body well above, piercing the water plane only with support struts to minimize the effects of waves. Sea-based Rectennas are anchored in place by cabling to the sea bottom. Dynamic tensioning of the anchoring cables enables an automatic positioning system to maintain orientation and position accurately with respect to the Rectenna's assigned location.

Power received is stored in an SMES and transmitted by

cable as needed to the electrical grid. Depending on the location of the Rectenna, hydrolysis of sea water to hydrogen and oxygen may also be conducted on site. Energy in the form of hydrogen serves the needs of portable, mobile and remote applications, and large-scale hydrogen production is an important function of ***Project Phoenix's*** energy replacement system.

Fig. 14
Sea-based Rectennas are supported well above the surface by flotation elements well below the surface. Wave forces at the surface are minimized, and stability is greatly improved.

Environmental concerns regarding microwave energy transmission take three forms: worry about biological effects of the radiation, concern that beams may drift away from the Rectennas, and uncertainty about electromagnetic interference. For large scale applications such as suggested by ***Project Phoenix,*** concern for the addition of heat to the atmosphere may be added. The concerns are real and have been considered in several studies over recent years.

Power transmitted to a Rectenna is tightly restricted to a conical beam. While the power density at the center of the Rectenna may reach 23 milliwatts per square centimeter, at the edge it will only be 1 milliwatt per square centimeter, and at a distance of 2.5 kilometers away from the Rectenna, it will only be .08 milliwatts per square centimeter. Safety standards in the United States and the western world allow up to 10 milliwatts per square centimeter. The major effect of exposure in the range above 10 milliwatts per square centimeter is believed to be heating. Birds flying through the beam would experience some elevation of body temperature. Passengers in an airplane should be more than

Fig. 15
Rows of parabolic microwave reflectors trap microwave energy and reflect it to rows of collecting antennas.

adequately protected by the aircraft's metal skin and the short time of passage. Sea life below a sea-based Rectenna are sheltered by the reflector/collector units.

The beam from the SPS is triggered by a signal sent from the center of the Rectenna. This signal provides the necessary

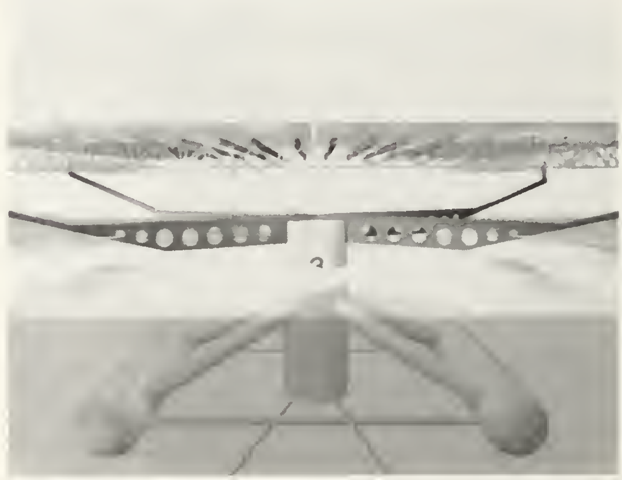


Fig. 16
SWATH (Small Water-plane Area Twin Hull) technology holds the Rectenna high above the water surface with minimum wave resistance.

phase control to produce a coherent beam. If the beam were to drift, its coherence would be lost and its energy would be dissipated to levels approximating normal communication signals on Earth.

The high power of the beam can potentially interfere with radar, microwave and radio frequency communications. For this reason, Rectennas need to be located away from traffic areas.

NASA studies indicate that heat released by microwave transmission of power to a Rectenna would be in the order of 15 watts per square meter. Some values for comparison are: 4 for a suburban community, 600 for a large industrial city, 100 for a thunderstorm or normal lake evaporation and 100,000 for an erupting volcano.

Conclusions

As ***Project Phoenix*** demonstrates, there are positive options available for confronting the problem of global warming. In fact, antidotes for global warming could also speed a successful transfer to other energy sources before fossil fuels run out.

Problems that take centuries to create will not be wished away or solved by scattered local and individual efforts. They require orchestration on a national and international level and on a scale that will inherently take time. The sheer size of the effort will require sacrifice by all. To bring recognition and consent for the massive effort required, the international public will have to be shown the options. The design disciplines have a critical role to play here in conceptualizing and visualizing these options for both leaders and public.

The Greenhouse problem should be treated as an insurance problem, not as a public works problem. If action must await proof of necessity, proof may take too long. Action as insurance, although bought under uncertainty, will justify the risk in the worst case -- and, if well conceived, will show benefits in any case. Best of all, well-conceived projects have the potential for contributing to the world economy and world well-being.

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SPS 91

C1.12 Inflatable Hose Structure Parabolic Antenna for Space Applications

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The suggested antenna contains two principal elements, namely, a paraboloidal mirror of wire mesh or metallized film and a supporting inflatable hose mat for the mirror dish. The mat with the attached mirror is collapsed and stored in a container for delivery to a space orbit.

The supporting mat is designed as a structure of a continuous plastic hose assembled from a number of rings with diminishing diameters ("sleeping snake" shape). Being inflated the mat acquires the paraboloidal form. Inflating gas pressure is rated between 0.001 - 0.0001 atm. The material is metal-coated. A wall thickness of the hose is about 1 mil (0.025 mm) or less.

A total weight of a 100 meter antenna is about one metric ton. Durability of the material should provide 10-15 years of the antenna life in space.

C1.13 About the possibility of power supply of spacecrafts by ground laser beams

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ABSTRACT

Using experimental results and estimations the possibility is shown of providing an average power of 100 kW on board a spacecraft by means of a ground-based laser station with average laser power (400-500 kW). Atmosphere transmission, cooling on board, safety, demands of a laser stations and spacecrafts network have been taken into consideration.

A conception is considered of a global non-electric solar-laser space system to provide the total power of 10 TW onto Earth. Projects are suggested of full-scale experiments for the integrity of key technologies.

RESUME

Sur la base des données expérimentales et estimations, la possibilité est montrée de fournir à un appareil cosmique à l'aide d'une station terrestre laser d'une puissance moyenne (de 400-500 kW) la puissance électrique unitaire de bord de 100 kW. On a tenu compte de la traversée de l'atmosphère, du refroidissement, de la garantie de sécurité, des exigences pour le réseau de station terrestre lasers et des appareils cosmiques.

La conception est examinée d'un système global non-électrique solaire-laser spatial pour l'approvisionnement de la Terre en énergie jusqu'à 10 TW. Les projets de grandes expériences pour la mise au point des technologies de base sont proposés.

Introduction

Among the most important problems to be resolved during initial stages of space investigation there was sufficient power supply for operation of equipment on board, and later - for a life support system and for experiments. The godsend was the application of solar energy, transformed to comfortable form of electric energy.

Then the branch of isotop and nuclear sourses have been formed. Not colling in question the possibility of their application during long space flights, it is necessary to note their purely tactical vulnerability in near future because of influence of public opinion.

Energy necessity of spacecrafts are increasing very rapidly. According to estimation made by French colleagues in 2010 the overall power on board about 10MW will be necessary. If it will be provided by solar cells, then there is a whole complex of technical problems (difficulties of spacecraft control with

increasing of the solar cells area), and economical problems (the cost of solar cells and their putting into orbit increases ~ 100 times).

Conception and estimations

An attractive possibility to provide spacecrafts by power from Earth surface is at the same time a very difficult problem. The main obstacle is to find the way of effective, stable and inexpensive power transmission.

Without a detailed review of different versions of such systems we can note, that taking into consideration the state of art in science, technology and industry an attempt is well-founded to use laser systems for this purpose.

For the last thirty years lasers became not only a new branch of science, but also very useful devices and equipment. High power lasers, means of diffraction-limited laser beams forming, optics for laser energy relaying have been created during this period. The efficiency is increasing till now for various kinds of lasers. Effective spectral transformers of radiation, control means of spatial and angular laser parameters are under design. Transmission of laser radiation through the atmosphere is investigated in detail.

The simplest model of a spacecraft power supply channel could consist of a laser station with an optical system for laser energy transmission, on board optical receiving system for laser beams, on board energy converter and cooling system.

Optics

Diameters of an on board optical system d and ground-based optical system D are connected by a simple relation:

$$d * D \geqslant \lambda * L,$$

where L is a distance between the spacecraft and the ground-based laser station, λ is a wavelength of laser radiation for energy transmission.

Fig. 1 is a dependence of the lower limit of this relation in the parameter region under discussion. For the comparison an estimation for microwave range (λ = 1 cm) is shown.

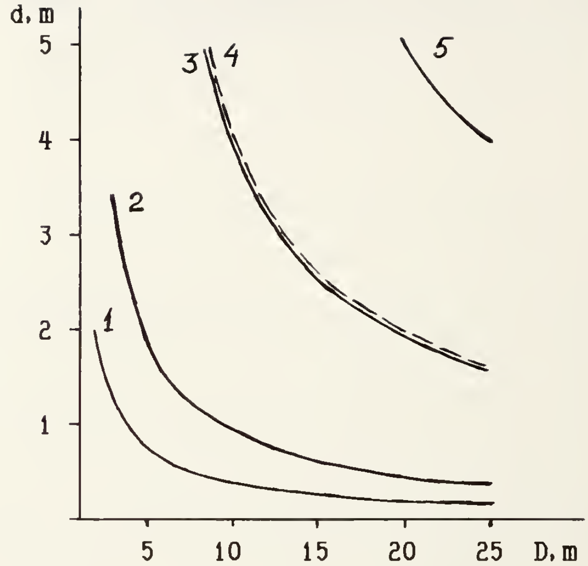

Fig. 1a - Dependence of a diameter d of on board optics on an effective diameter D of the ground-based laser station. 1, 2, 3. λ = 1μ 4, 5. λ = 10μ. 1, 4. L = 4000 km. 2, 5. L = 10000 km. 3. L = 40000 km.

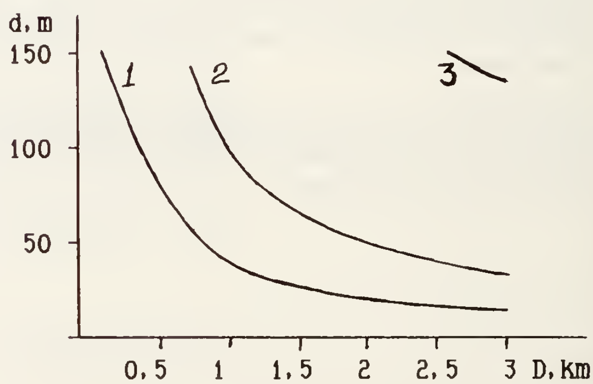

Fig. 1b - Analogous dependence for microwave range. λ = 1 cm.
1. L = 4000 km. 2. L = 10000 km.
3. L = 40000 km.

Diagrams clearly show, that in practice the realization of such an optical pair even for a relatively small λ = 1 is an extremely complex problem (seeming simplicity of the situation for low orbits will be dicussed a bit later). It is almost evidently, that the ground-based optics must be a composit design providing the phase coupling between its subapertures. In this case the estimated diameter means an effective value.

Energy conversion and cooling

The task of convertion of laser energy on board of a spacecraft is nontrivial one. It is necessary to provide a heat balance on board taking into account the energy converter and the energy load efficiency. For an elementary estimation it is possible to assume, that all laser energy on board is transformed to heat by different ways. For average electric power P for the efficiency η of laser energy conversion to electric energy the overall radiators area is necessary for cooling

$$S > P/(\eta * \mathcal{E} * \sigma * T^4),$$

where $\mathcal{E}$ is the blackness coefficient of a radiator surface, T is the temperature of the radiator.

Fig.2 is the dependence of the radiator area on its temperature for P = 100 kW and $\mathcal{E}$ = 0,9.

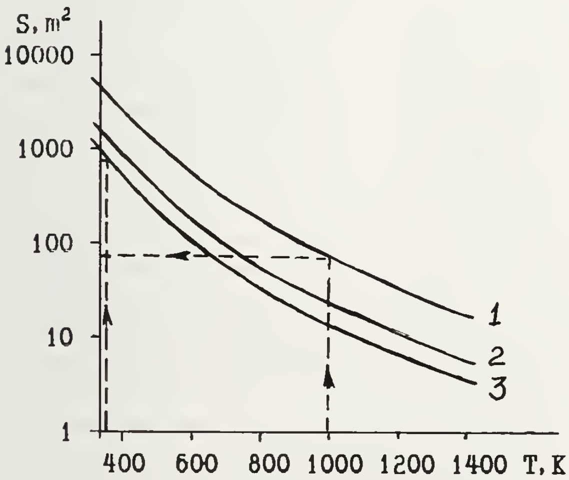

Fig.2 - dependence of the lower limit of a radiator area on operating temperature, where η is equal to: 1. - 0,1. 2. - 0,3. 3. - 0,5.

A photoelectric energy converter is the most suitable one. Some of heat energy converters may be used also. As a rule the efficiency of such a converter is less in comparison with the photoelectric converter there are maintenance difficulties. Nevertheless a comparison by parameter totality could lead to an advantage namely of such a version. For example assuming a difficult of achieve value η = 0,5 and upper temperature limit T = 350K for a photoelectric converter S = 940m^2 and at the same time for η = 0,1 and T = 1000K (a heat energy converter) S = 69m^2, hence about 14 times less (inspite of 5 times loss in efficiency). An advantage of this version depends on of comparison of less on board equipment cost of less cost of its putting into orbit and of more expensive ground-based laser station having 5 times more output power and of more expensive maintenance of such a station including an expenditure.

Certainly, the best way is to design a photoelectric converter with high efficiency and high operational temperature, that is not an unrealizable task.

A laser

Successful realization of this new way of power supply strongly depends on the choice of a high power laser. For an initial analysis the most technically advanced and experimentally investigated lasers may be suggested. There is large group of gaseous lasers with a continuous-wave chemical laser as a leader among them, operating with HF and DF-molecules (the "Miracle"-system in the USA). High power level ($\sim$2MW) is achieved combined with acceptable beam divergency. High power is also achieved with lasers on CO_2-molecules mixed with some other gases. Some schemes show beam divergency near the diffraction limit. Eximer, CO-lasers and some other types of lasers (e.g. ion lasers, metal vapor lasers and others) are also advanced, but to lower levels. Recently an oxygen-iodine continuous-wave chemical laser is actively developed, based on conversion of chemical energy to energy of excitation of J-atoms and of laser emission as a sequence (wavelength 1,3μ).

Solid-state lasers are successfully developed based on laser glasses and various crystals. The largest high-power solid-state lasers in the USA, USSR and Europe for laser fusion are well-known, and also a set of projects on average power 1MW and even more (for a difficult regime of short pulses). There is sharp increase of number of laser processing equipment, which confirms the possibility of commercial use of such lasers during long period. Industrial basis of solid-state lasers is well developed and this development is in pro-

gress till now.

A quite new branch of a laser science is the development of free-electron lasers. The principal possible advantages of these lasers concirning to the problem under discussion are high efficiency and high output power, not accopanied by optical distortions of active medium of a laser.

In my opinion it is necessery to show preference to a continuous-wave or quasi-continuous-wave multichannel solid-state neodymium laser as a basis for the first generation of ground-based laser stations. At least solid-state lasers, which have been put into production are useful for full-scale experiments for technology integration (although large scale of an equipment demands new schemes). The oxygen-iodine laser should be considered as a second candidate assuming, that industrial samples of such a laser will take place of experimental lasers of this type. The free-electron laser may be considered as a promising one. Success of this promise depends not only on power and efficiency increase, but also on the possibility of this laser to use multimode emission either by means of wave front wave conjugation, or by means of linear adaptive optics, which is necessary for compensation of optical distortion of the atmosphere and of optical subsystems and for realization of super-precision alignment.

Energy transmission by means of a laser beam

Energy transmission at a distance of thousands km from surface demands to overcome the unfavourable influence of an atmosphere on a laser beam. Atmospheric influence leads to increase of beam divergency ψ and, hence, its diameter (which is approximately equal to diameter of on board optical receiving system d) at the vicinity of a spacecraft to unacceptable value. For example, at a distance 40.000km for not so large value of additional angle of diverdency (because of atmospheric turbulence) ψ = 1 arc second

$$d \quad \psi * L = 200 \text{ m.}$$

Here the initial beam divergency at the laser station output have not been took into consideration at all.

A second factor - selfinduced damage of a laser beam in the atmosphere - makes it more difficult to receive laser beam by a spacecraft.

An influence of the atmosphere, extremely high demands to precision of alignment, necessity to avoid significant losses for imperfect receive on board of spacecraft lead to important limitation of possible schemes of laser energy transmission. Let us consider a version of scheme, which permits the best possibilities of energy transmission. There is forming optical system on board of the spacecraft, which transmits a beam of a master oscillator towards the input of a ground-based laser station. The master laser beam from the spacecraft meets the atmosphere only at the end of its part, and because of this reason the atmosphere can not have a significant influence upon intensity distribution across the master oscillator beam. For an effective optics diameter of a laser station 10 m and for additional angle of divergency 2 arc seconds (when the atmosphere thickness is 10 Km) spread of the master beam does not exceed 1% of the ground-based optics diameter.

The wave front of the master oscillator radiance at the input of the laser station includes the information about natural and induced inhomogeneities of the atmosphere. Ground optical forming system during the transmission of master oscillator beam towards the main laser amplifier "records" the system imperfections upon this wave front. At last the master oscillator beam passes through the laser amplifier and records the amplifier imperfections. Then the phase conjugate mirror (PCM) reflects the beam with exactly the same wave front (this phenomenon may be approximatly imagined as a reflection by a mirror having its surface, which exactly coinsides with shape of wave front).

When wave front of high power beam passes through the same path in the opposite direction, its form returns to the form of wave front of master oscillator beam. Thus there is the compensation of optical inhomogeneities along the whole path between the ground laser and the spacecraft by means of phase conjugation. Moreover, it is possible to suggest a

scheme version without any master oscillator on board and having all advantages mentioned above, and also the scheme version with a linear adaptive optics.

Safety

A natural question concerning of a safety problem is connected with such unusual way of energy transmission to spacecraft by means of high power laser beam. First of all let us note that any laser beams are impossible in all directions besides the direction to the receiving optics on the spacecraft due to technical features of the system, for the ground-based laser operates only after the laser "request" from the spacecraft and provides the exact return of the laser beam by PCM. The spacecraft is protected by the excellent interception of the laser beam with the optics. For example, to have electrical power on board 100 kW it is sufficient to have 300 kW laser power in the input. Assuming the co-ordination of optics diameters one can estimate loss 10% of this power or less. For optics diameter 2 m and the second diffraction maximum width 1 m the average power density in the vicinity of the optical system will not exceed 3 kW/m^2(the value is comparable with the solar illumination).
Between the laser station and the spacecraft the crossing of the laser beam by different objects is not excepted. For an other satellite the estimation gives the energy density less than 40 J/m^2. For an aircraft the energy density is less than (200 - 400) J/m^2, though this situation is preventable one by organization means.

The integrating experiment and the estimation of the network

Thus, the up-to-date state of affairs in space and laser engineering, in optical industry permits to suggest the full-scale experiment to confirm and develop the principal technical decisions of the project: creation of the ground-based laser station (may be two stations) with average output power (400 - 500) kW, of the special satellite with sufficient optics, with master oscillator and with the energy converter for electrical output power (100 - 150) kW and carrying out of long-term tests and investigations in real conditions. The full-scale experiment can be anticipated by ground-based experiments to investigate subsystems and to model their interaction.
Nevertheless it is important to notice that now there is quite sufficient level of parameters and technique, which permits to substantiate the full-scale experiment:

- Average laser output power is about 1 MW,
- There are high power multi-channel lasers,
- There are laser heads with high average power,
- The large success have been achieved in solid-state diode-pumped lasers - one of the main versions of lasers with the large life-time,
- The possibility of phase coupling of laser channels in the multi-channel laser is experimentally confirmed using PCM,
- Phase coupling of a composite optics with the effective diameter up to 2 m have been achieved, which provides a diffraction-limited total beam also using the PCM,
- Compensation of optical inhomogeneities because of atmospheric turbulence have been achieved using phase conjugation,
- Methods for compensation of the spacecraft displacement during the light propagation from the spacecraft to the laser station and backwards are suggested and experimentally confirmed.

Assuming the success of the full-scale experiment it is interesting to estimate the headmost laser surfac-espace network. The possibilities of a single system "a spacecraft- ground-based laser station" are significantly limited by the high probability of influence of clouds and by time limitation of being within view (besides the geostationary orbit). It is expediently to create the laser power supply system as the ground-based laser stations network, which in concord provides the satellites network. Moreover, it is difficult to provide the low-orbit satellites directly even by the station network (because of large num-

ber of laser stations - near 2000, of the more complex control system and of obstacles made by clouds). It may be very possible for this category of satellites, that the middle- or high-orbit laser energy retransmission system will be preferable.

Reserve subsystems are necessary in various parts of the network to stabilize the power supply (energy storage on board of a spacecraft to provide the power supply during the switching from one station to another, one reserve laser channels within the laser station, reserve laser stations at various regions of surface).

To provide the total power 10 MW on board of all satellites near 100 satellites may be used. It is necessary to have(120 - 125) laser stations with the total power about 50 MW (taking into account losses in the atmosphere and in the power converter on board). Each ground-based laser (the most probably - multi-channel with the unit power less than 100 KW must generate (400 - 500) KW To have this output power one must have (12 - 15) dm^3 of active laser medium, and for the network as a whole - about 1800 dm^3. This value of laser crystals may be prepared providing the principal decision to create the network.

The estimation of other subsystems shows that such a network would be a reality in the near future. At least the development of a new generation of the space telecommunications (audio, TV, video-communications, computer networks with space feeder lines, various safety systems), the development of power-consuming industries in space could be supported by the new generation of a power supply network.

Prospects for global power engineering

Next generations of the system considered would be very useful during the creation of a global "space - Earth" power engineering system. Energy on board of satellites, which will be delivered by laser beams, may be used for inexpensive putting into high orbits of various constructions.

It is almost evident, that the energy supply sources must be space-localized. Besides the principal ecological advantage providing the acceptable cost, the global space power engineering system would useful for some special kinds of power consumers (spacecrafts, above-water ships and air fleet with direct power supply from space, remote stationary consumers, launch systems and space transportation).

Global ground-based solar power system would competitive with the space-based one. But the ground-based system demands more materials, is vulnerable to wind, precipitations, degradation reflectors, that leads to more expensive energy.

Solar space power engineering system has advantage in comparison with the space nuclear and fusion versions because the absence of nuclear fuel and waste products. Moreover, common sense advises, that first of all one must try to use the energy, which always and at enormous values is produced as a result of the same reactions inside the Sun. It would be better than the repetition of these reactions once more and overcoming of obstacles, accompanying this way.

Global solar power engineering also demands to resolve a number of very complex problems, the most of them are connected with the transmission of energy to consumers. They includes solar energy conversion and transmission of converted energy along the large-scale distances. Any source of energy in space leads in practice to one of two ways: transmission by microwaves and by laser beams.

Laser beams as an energy feeder are very suitable, and the method of transmission is almost the same as above mentioned one, but the "laser request" must be produced from the ground-based power receiving station. There is unique possibility to convert solar energy directly to laser energy. The efficiency of this process may be forecasted near (5 - 8)%. Putting into orbit of heavy power engineering equipment is excluded in this method. Heat power in the laser is equal approximately to (30 - 50)% of laser output power at operational temperature (500 - 600)K.

To have total power at the Earth about 10 TW it is necessary to have $\sim 2*10^5$ m^3 of laser active medium. Equivalent field of film reflectors

(most probably inflatable) would be sufficient 450*450 km. If the cost of the putting into orbit per 1 kg mass will be brought down to 100$, then for the total number of lasers the cost of their putting into orbit is $100 billion and for reflectors - $1000 billion. The area of radiators is (100 - 150) times less than the area reflectors. Assuming the thickness of a radiator 0,5 mm one has the cost of their putting into orbit near $150 billion. Obviously the overall cost of this global program can exceed $1500 billion. Nevertheless this cost to be paid for a decision of the global power supply problem and of significant part of ecological problems does not look excessive (approximately 5$ a month per each person during 5 years).

The solar-laser version has its own distinctive features:

- An effective sun-pumped laser with (15 - 20) years life-time,
- Film reflectors with unit area near 1 km^2, having the selective reflection and means of forming in space (also for the aspheric surface), e.g. by electrostatic or other fields,
- Control system for the reflector alignment to laser-converter (angular transverse and longitudinal coordinates),
- The laser alignment to the ground-based receiving station, forming of diffraction-limited laser beams,
- Effective converters of laser energy to other kinds of energy at the ground-based receiving station.

The way out of an ecological and energy crisis by means of solar-laser power engineering has a basis and prospects no less than fusion, which is the most actively developing till now. Moreover, investigations on the space solar-laser power engineering could lead to more early beginning of real power supply of consumers, than the fusion could, and ecological after-effects of the full-scale development of the solar-laser power engineering may be estimated as more acceptable.

Total value of various materials would be near (10 - 15) million tons, overall value of materials and of fuel for putting the system into orbit would be near (50 - 20) million tons in a favorable case, and the operation of the system is quite pure. Due to these features it would be correct to organize this program as well as it have been done for the fusion program, including the financing.

For similar reasons it is expediently to suggest to prepare the large-scale international project "Laser-Solar Power Satellite"(L-SPS), main points of which would be the program of ground-based investigations, design and production of devices and equipment, model experiments and the full-scale experiment on energy transmission to the ground-based receiving power station. Level of power in this experiment would be estimated during the elaboration of the project.

Conclusion

The possibility is considered to create the ground-space laser system for power supply of spacecrafts. For unit on board power 100 kW the ground-based laser station must have the output power (400 - 500) kW. The full-scale ground-space experiment is possible in near future as a basis for the commercial power supply system design. Main parameters of such an experiment are estimated.

There is principal consideration of ways out from the energy problem by means of direct conversion of solar energy to laser energy in space and of transmission of laser energy to ground-based electric power stations. Main estimations show that this global problem could have a decision. The project "Laser-Solar Power Satellite" is suggested - the full-scale experiment to confirm principal technical decisions and to integrate technologies of energy transmission from space.

Thus the extremely complex problems are considered. Nevertheless the attractivness of decision of these problems significantly exceeds their difficulties.

C1.14 Constructions and ground testing of large high precision space structures

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ABSTRACT

In this paper, the authors present the studies and tests concerning the development of large, high-precision space structures. In particular, this report describes the theoretical and engineering studies, and the manufacturing and testing of these structures, as well as full-scale structure testing.

RESUME

Dans cette communication, les auteurs présentent les études et essais concernant la mise au point de grandes structures spatiales de haute précision. Ce rapport détaille en particulier les études théoriques, les études d'ingénierie, la fabrication et les essais de ces structures, y compris les essais en vraie grandeur.

Obtaining the space energy is a part of a huge problem the humanity is facing nowadays and which,at a general look,represents an industry and construction engineering in the space.

The problem, as a whole, as well as specific parts thereof virtually always reduire certain engineering support, i.e. erection of carrying, reflecting and other large-sized structures in the orbit. It is exactly the Institute of Transformed Structures that carries out research,design manufacturing, ground testing and supply of launchable prototipes.

The works are performed in an aggregate manner which contains several trendswhich define, on the whole, structures assembling in the space.

The trends are as follows:

1. Principles for structures shaping formation in limiting conditions;
2. Development of the structure classes set for specific tasks, namely, large technological sites, concentrators,large-sized antennas, long-sized elements etc.;
3. Theoretical studies preceded by experimental works over scale models and structure pieces and the optimization model creation.

This part of studies is essentially comprised of the following three stages: the structure transportation stage behaviour's math simulation, unfolding and space operation.

4. Design of the structure system with a release of technical data kit for the produce;
5. The structure system's manufacturing and assembling,maintenance;
6. A full-set testing on the experimental structure prototypes with a real-enviroment modelling;
7. Updation of technical data documentation and supply of prototypes to be launched.

A particulary important trend out of the tasks set forth is the one for developing of construction principles and creation of the ground-testing complexes for large-sized space - based engineering structures.

1. Principles for structures shaping formation in extremal conditions.

The space structure shape formation is a principal criterion for implementation of the engineering task. The shape formation process has many constraints and it is not entirely dependent upon the parameters required for the large-sized space structure. The constraints may be of quite a versatile nature, however, the basic ones are as follows: limiting sizes of the [illegible]

VII. Updation of technical data documentation and supply of prototyps to be launched.

After the stage-by stage completion of the working prototypes creation, the following prototypes have been created to be launched:

7.1. The space radiotelescope 30 m in diameter the folded transportable pack of which is shown in Fig.5;

7.2. The large-sized pneumorigid unfoldable structure of the reflector (Fig.6);

7.3. The "Kolkhida" long-sized unfoldable power structure (Fig.7);

7.4. The technological site (Fig.8) which is now being tested in the cosmonautory by S.Kricaliov and A.Artsibarsky in the "Mir-1" station;

7.5. The most important stage of the new generation structure creation is the ground-based quick movable truck-mounted radiotelescope for emergency communication with the space-based objects(Fig.9)

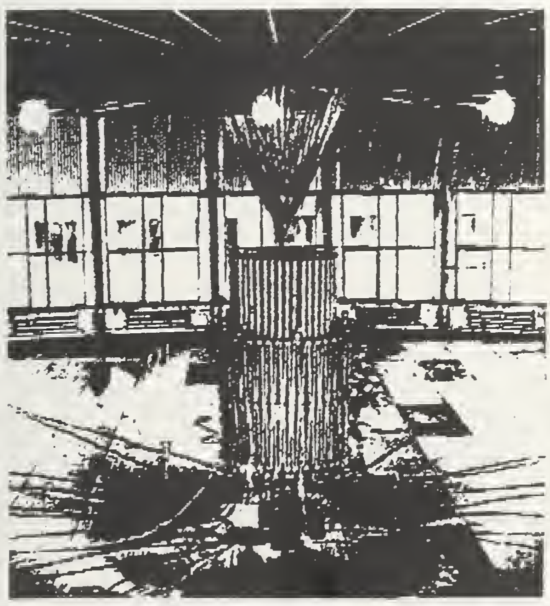

Fig.5. Transportable pack of space radiotelescope 30 m in diameter

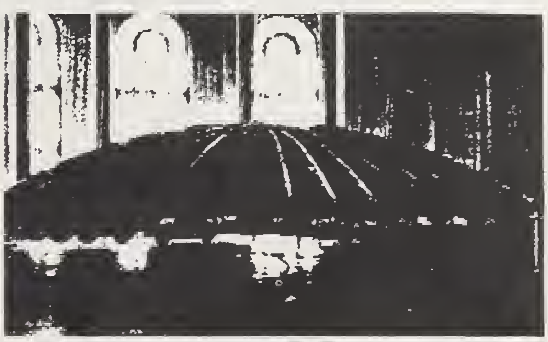

Fig.6. Pneumorigid unfoldable power structure

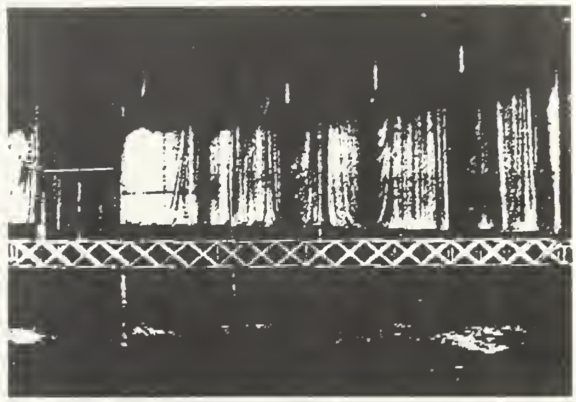

Fig.7. The "Kolkhida" unfoldable power structure

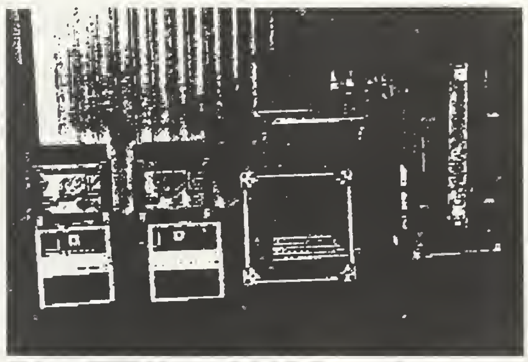

Fig.8. The technological site on "Mir-1" station

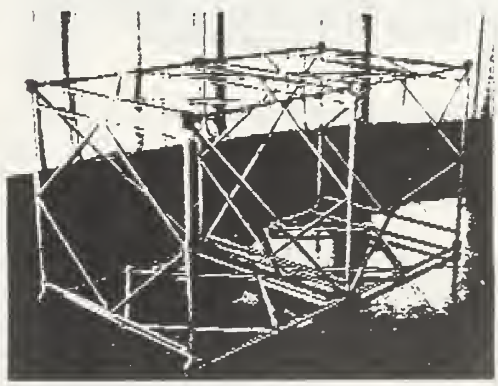

Fig.10. The unified transformable cristall

A distinctive feature of the structures under designed and, primarily, of the space power installation, in contrast to conventional engineering structures, lies in their high level of precision. The geometrical precision of such systems is expected to be, in most cases, 100 tymes higher than that of usual ones.Solving such problems in the space is to be quite a job, let alone the Earth. Therefor, a biased, unilateral approach to the problem solving can not give positive results. This is attained only on the bases of an aggregate approach and thorough development of separate trends, which have been men-

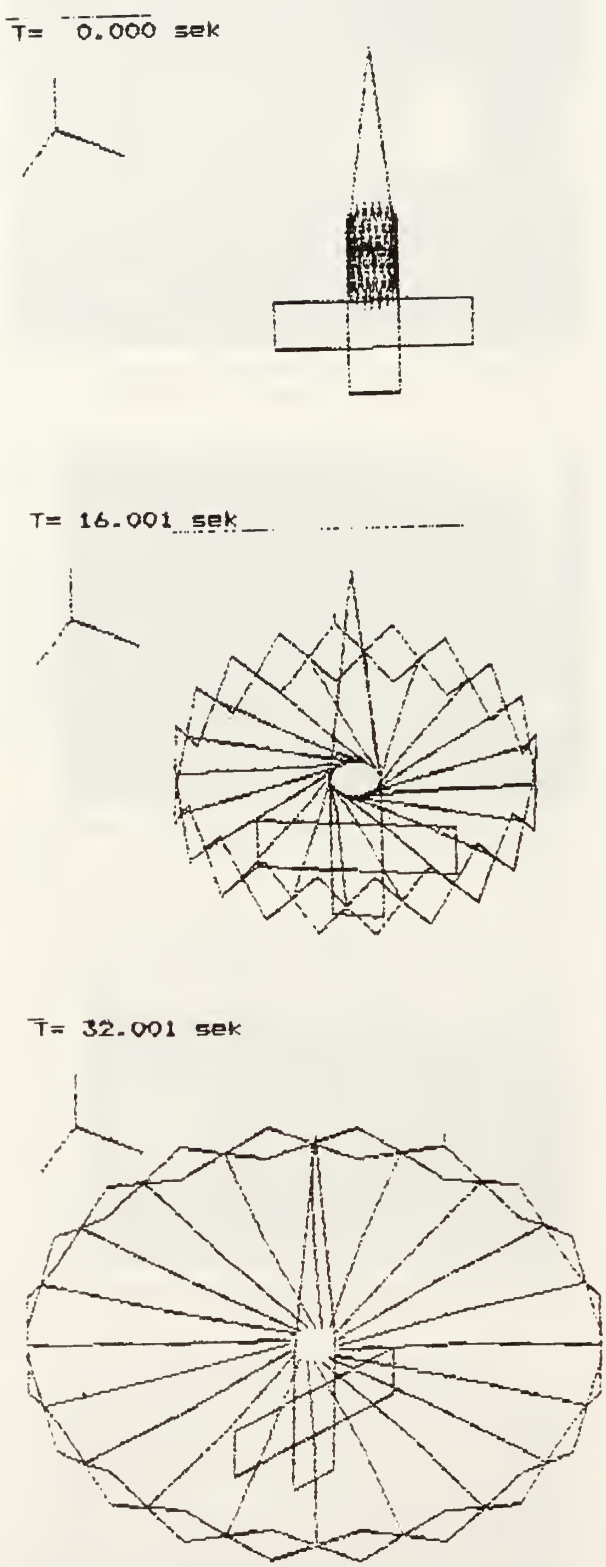

Fig.1. Space antennas unfolding process in normal mode

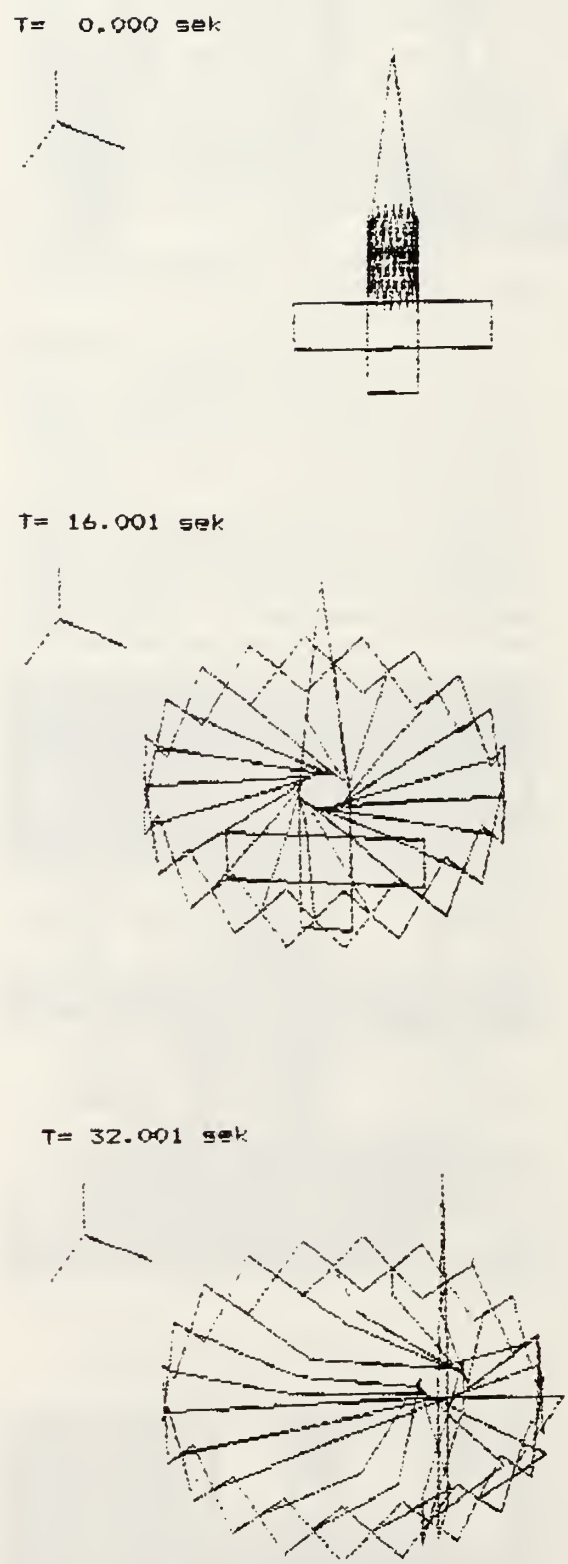

Fig.2. Space antennas unfolding process in abnormal mode

20 m long;

5. The unified transformable crystal for construction of large space sites with prestressed carrying system intended for easier assembling in the orbit and enhancing both rigidity and geometric precision of the structure parameters. The crystal is helpfull in constructing carcasses of any geometrical configuration and sites of virtually any shape and size;

6. The pneumorigid structure of the space radiotelescope up to 50 m in diameter;

7. The ground quick-movable truck-mounted radiotelescope for emergency communication with the space-based objects. The aerial reflector diameter is 12 to 15 m.

V. The structure system's manufacturing and assembling maintenance

Both experimental and launchable prototypes are manufacturing by the institute in collaboration with the Tbilisi Industrial Amalgamation for Aircraft Manufacturing (Republic of Georgia). To these ends, the Amalgamation offers the freshest technologies by using which the parts and units of the structures are manufactured. Assembling procedure is carried out at a dedicated test bench available at the Institute. The test bench is supplied mith high precision instruments for assembling control as well as with a sensitive system of the weight annulment of the structure as a whole as well as its parts. A high-skilled team of the mechanical engineering technology, aircraft engineering technölogy, programming,material and metrology experts is involved in the manufacturing process.

VI. A full-scale structure testing

The trend mentioned is the most important one in space unit construction and requires tackling down of the complex technological problems via development of the test benches with imitation of weightlessness and other suchlike space parameters and also asks for huge finance and ma-
cumentation and supply of pro-
terial resource expenditures,high
totypes to be launched
skilled manpower and energy re-

sources . The Institute has desi-
After the stage-by-stage comp-
gned and implemented a unique ground testing complex for the space-based large-sized structures and radioelectronic systems (Fig.3).

Test complex consists:

- 40 m diameter structures precision assembly jig with high precision mechanical weightless and testing systems, 1200 m floor area with controlable surface, 40 m diameter and 20 m height hydrobasin for testing space stuctures in hidroweightless conditions;
- 40 x 40 m size and 35 m height transpose stand equiped with testing and weightless systems;
- turnable stand for space 30 m diameter retractable radio telescopes ground testing in ground fullturn radiotelescope mode;
- labaratory and utility blocks, up-to-date instumental test equipment large stock and other necessary services.

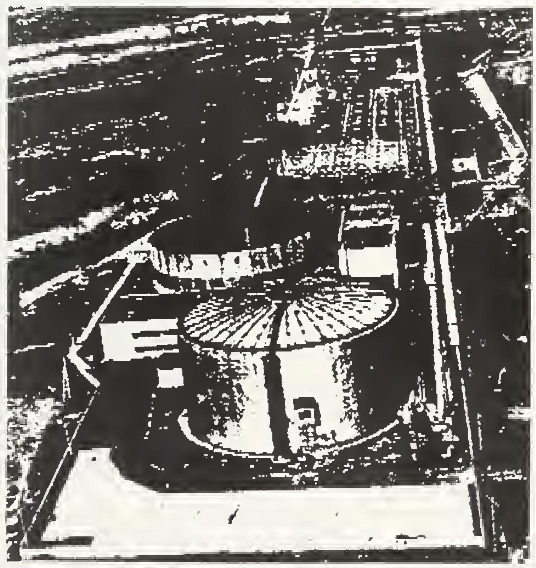

Fig.3. Testing complex for the space-based large structures and radioelectronic systems

Along with the Institutes works, other ground tests are held at this base, with due regard for the interests of other spase companies of the USSR. In 1988, experimental works were carrid out over two ring antenna unfoldable structures 20 m in diameter each. A space experiment called "Crab" was conducted on the basis of the works done (Fig.4).

Fig.4. Space experiment "Crab" in 1989 year

tures to be launched; their weight; shape construction processes which at times require a certain level of automation; open-space works of astronauts, robots or manipulators.

Any space-related task solving is still a complex and consuming process nowadays. On choosing a shape formation process for a specific structure the following techniques should be a matter for consideration:

- -a collapsible one;
- -a collapsible-transformable one;
- -a transformable-collapsible one;
- -a technological one;
- -a solely transformable one.

In most cases, an optimal combination of the enumerated techniques will be applicable depending upon a specific task. In this direction, theoretical studies with a bulk of attention being made on the transformable systems have been conducted to classify logical foundations for the shape formation processes with a purpose of a math simulation and geometrical systematization of the shape formation as well as for determining of the physical factors of the process (look Medzmariashvili E., Transformable systems, USSR Academy Science, Tbilisi, 1990).

II. Development of the structure classes

The following pieces have been developed at the level of invention, draft designes and operating prototypes: new efficient classes of structures of large space antenna operating within the centimeter to meter wave range the aerial reflector diameter exceeding 30, 50 m and more; concentrators with high precision surface up to 13 m in diameter; super-large solar batteries and different-type reflectors; large-sized carrying carcasses of the large space sites and platforms; long-sized elements with space between consoles exceeding dozens of meters and the ground quick-movable receiving devices working in conjuction with the space systems.

Development of the constructive classes is based on the novel approaches: creation of structures with unilateral joints, ring systems, pneumo-rigid structures, based on the prestressed principle as well as many other innovative approaches the part of which originates from the best traditions of the ground civil engineering while the rest are unique ones.

III. Theoretical studies

The studies sphere covers the problems of the math simulation of the space structure unfolding with regard for all-round analysis of the process dynamics and for creation of the engineering structures operation behaviour math model.The software package contains the following parameters: standalone processes temporal intervals; the structures abnormal behaviour; alteration of the system's geometrical parameters; oscillation frequency and amplitude; element's strength, local and universal stability etc. The package ensures a display of numerical and graphics information and the process animation on the screen. For example, Figs. 1 and 2 show the printouts of stills of the antenna unfolding process in abnormal and normal modes.

IV. Design of the structure system with a release of technical data kit for the produce.

Presently,the following structure system technical data kits have been released and implemented on the bases of development of this trend:

1. Space radiotelescope 30 m in diameter working within decimeter and meter wave range. The weight of the metallic version of the antenna proper is 750 kg, the composite materials version of the antenna is 470 kg. Unfolding time is 45 seconds. Dimensions of the cylinder-shaped pack are: diameter -1.8 m; height - 2 m. The unfold mechanism of the reciprocally duplicating systems is made in the form of the accumulating forces of elasticity and motors;
2. The space radiotelescope with the aerial reflector diameter of 30 m working in the centimeter wave range.The weight of the metallic version of the radiotelescope proper is 1100 kg, the composite materials version of the radiotelescope is 850 kg. Unfolding in the space is 25 sec. The dimensions of the folded transportable pack are: diameter - 2 m, height - 2,1 m. The unfold mechanism is; the reciprocally duplicating electromechanical systems and the accumulator-based version of the elasticity forces;
3. The space radiotelescope of improved precision and rigidity 30 m in diameter.The weight parameters increase in comparison with the version 2 by 15% -17%. The rest of the parameters are the same;
4. The "Kolkhida" long-sized unfoldable power structure up to

tioned in this paper, those which are under development at the Institute of Transformed Structures of the Georgian Technical University.

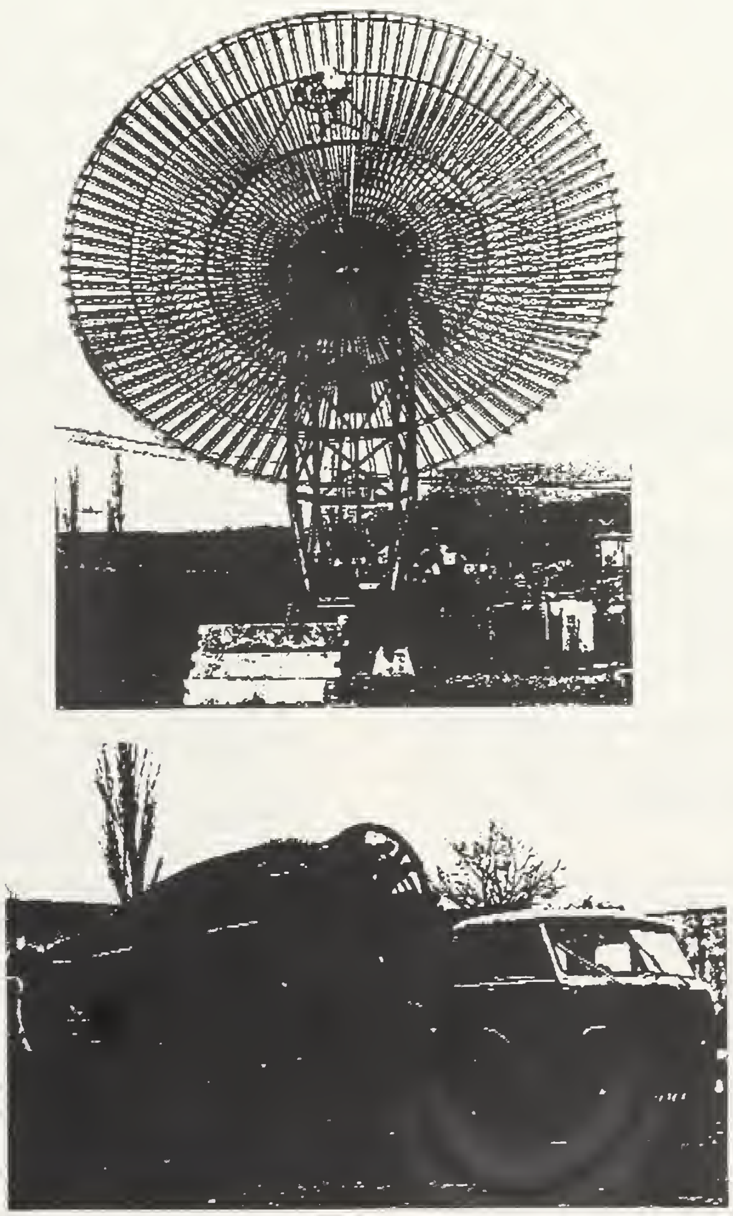

Fig.9. Ground-based quick movable truck-mounted radio-telescope for emergency communication with the space-based objects.

C1.15 The legal regime of the Moon regarding the exploitation of natural resources

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I.

The Solar Energy from Space and Moon Scenarios affecting the Legal Régime of the Moon

Reading the NASA report on Lunar Energy Enterprise Case Study Task Force of July 1989, it appears that the legal issues arising under the concepts Solar Power Satellite and Lunar Power System as described therein and briefly summarized as follows were treated as the DARK SIDE OF THE MOON.

1. The Solar Power Satellite (SPS) Project

SPS does not require, from a pure technological perspective, a return to the Moon. The object and purpose of SPS is to convert solar energy in space for use on Earth. Microwave or laser beams would transmit the power generated by SPS in the geosynchronous Earth orbit to large scale rectennas receiving the energy on Earth. However, the establishment of a lunar base and the development of processing technologies for lunar materials would promote the economic success of SPS considerably. Furthermore, the transportation of required materials for SPS from Earth on a scale required to build up a global SPS system may result in environmental damages from propulsion by-products. Since less energy is required to move mass from the lunar surface to the geosynchronous Earth orbit than from the Earth's surface to the same orbit, it may become vital for the economic and environmental feasibility of SPS to consider the exploitation of appropriate materials for the construction of the SPS from the Moon.

The Moon's natural resources, such as metals, glasses and oxygen appear to provide materials for the construction of the system of solar power satellites in the geosynchronous orbit. If processing and the transportation of materials from the Moon to the geosynchronous orbit could be performed at costs competitive with those for terrestrial materials, more than 90 per cent of mass of SPS could be mined, refined, fabricated and transported from the Moon.

If placed near the Moon, SPS could also serve as a power station providing energy for a lunar base.

2. The Lunar Power System (LPS) Concept

The LPS is likewise based on a microwave power-beaming concept using the Moon rather than Earth-orbiting satellites in order to collect and to transmit power. LPS may collect solar energy at a lunar power basis located on opposing limbs of the Moon. Each base contains solar converters and microwave transmitters transforming the solar power into microwave power which is beamed to receivers on Earth and in space, which convert the microwaves to electric power. NASA's estimates suggest that only 10 per cent of a ton of components and consumables would be required from Earth to implace one megawatt of received power, whereas most of the components of the base would originate from lunar materials. Whereas a given base on the Moon is adequately illuminated only about half of the days of the lunar month, large mirrors, so-called "lunettas" will be placed in the orbit about the Moon and orientated so as to reflect sunlight to the bases in order to keep the lunar bases illuminated and delivering power continuously. Such a lunetta, which is in essence a solar sail, will be constructed primarily of lunar materials.

The LPS is a very complex concept. By supplying power to the lunar base itself the veil of the commercialization process of the Moon will definitively be lifted in regard to a large scale exploitation of its natural resources, inter alia, its big resources of Helium-3 on the surface of the Moon, estimated to satisfy the world's current electric energy needs for over 1000 years.

How do these projects correspond to the legal régime of the Moon ?

II.

As to the Sources of the Law Governing Activities on the Moon

The "Agreement Governing the Activities of States on the Moon and Other Celestial Bodies" of December 18, 1979 (the "Moon Treaty") which came into force on July 11, 1984 reveals in its Article 11 para. 1 the very raison d'être of the Treaty:

"The Moon and its natural resources are the common heritage of mankind ...".

Whereas the preceding 1967 "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies" provides in its Article I that the space environment and its natural resources may be freely and equally explored, exploited and used by all States, Article 11 para. 7 (a) to (d) of the 1979 Moon Treaty stipulates:

"(a) The orderly and save development of the natural resources of the Moon;

(b) the rational management of those resources;

(c) the expansion of opportunities in the use of those resources;

(d) an equitable sharing by all States Parties in the benefits derived from those resources, whereby the interests and means of those countries, which have contributed either directly or indirectly to the exploration of the Moon, shall be given special consideration".

To safeguard the implementation of the common heritage of mankind principle and the concept of an "equitable sharing" Article 11 para. 5 and Article 18 of the 1979 Moon Treaty authorize the

States Parties to the Treaty to establish "an international régime, including appropriate procedures, to govern the exploitation of the natural resources of the Moon as such exploitation is about to become feasible". This "progressive development" of international space law has opened a pandora box of difficult questions:

Who is to determine whether sharings are "equitable" ? Does the provision for an international régime mean a de facto moratorium regarding the exploitation of natural resources on the Moon until the establishment of such an international supervisory body ? Which supervisory and administrative functions shall be granted to the executive body of such an international régime and how shall it be composed ? Do the inroads on the free enterprise system implied in the common heritage of mankind concept cause a State to lose all, or at least, restrict its exclusive jurisdiction and control over national space programs, objects, and personnel while in space ? To what extent could the international régime in question affect the project "POWER FROM SPACE" ?

III.

As to the Impact of the Legal Régime of the Moon on the Project "POWER FROM SPACE"

The common heritage of mankind principle enshrined in Article 11 para. 1 of the 1979 Moon Treaty has been developed in connection with the codification activities concerning the progressive development of the Law of the Sea, and to a lesser degree in connection with the legal régime of the Antarctica, within the institutional framework of the United Nations General Assembly. The preamble of the 1982 Convention on the Law of the Sea refers to United Nations General Assembly resolution 2749 (XXV) of December 17, 1970, which solemnly declares that the area of the "sea-bed and the ocean floor and the subsoil thereof beyond the limits of national jurisdiction, as well as the resources of the area, are the common heritage of mankind".

This idea is accentuated in Article 140 of the 1982 Convention on the Law of the Sea, according to which activities on the sea-bed, the ocean floor, and the subsoil thereof beyond the limits of national jurisdiction shall, as provided for by the régime on the deep sea-bed, "be carried out for the benefit of mankind as a whole, irrespective of the geographical location of States" and "taking into particular consideration the interests and needs of the developing countries". According to Article 137 of the 1982 Convention on the Law of the Sea no State shall claim or exercise sovereignity or sovereign rights over any part of the sea-bed and the ocean floor or its resources, nor shall any State or natural or juridical person appropriate any part thereof. The 1979 Moon Treaty follows in its Article 11, at least conceptually, the same approach. The common heritage concept implies a revolutionary element of the new public international law providing that the control of resources of a former "res nullius" becomes "res communis" and is vested with mankind as a whole. According to Article 157 para. 9 of the Convention on the Law of the Sea, mankind in turn, is represented by the Sea-Bed Authority which is the administrative body through which States Parties to the Convention organize and control deep sea-bed activities as trustees on behalf of mankind. In addition the régime of utilization establishes the obligation for all States to cooperate internationally in the exploration and the use of the sea-bed and the ocean floor. This régime of cooperation intends to realize equal participation of all States, the

sharing of revenues, and transfer of technology in order to enable equal participation, preferential treatment and the protection against adverse effects. The 1982 Convention on the Law of the Sea provides for substantial restrictions imposed upon potential deep sea-bed miners, affirmative action benefitting non-mining States and in order to control and to administer these objectives confers jurisdiction over deep sea-bed mining on the Sea-Bed Authority wherein all States Parties to the Convention can participate. As means to achieve an equal distribution of the resources of the sea-bed, mainly two different concepts are discussed in the absence of a specific provision for distributive justice: either a system of preferences or a scheme of compensation. This common heritage régime has been the main hinderance for industrial States with developed technologies in sea-bed mining, inter alia, the Soviet Union and the USA, to ratify the Convention on the Law of the Sea, whereas for the developing countries common heritage of mankind appears as manna from heaven. It is obvious that such an order is likely to jeopardize commercial investors involvements in the projects as suggested by the NASA report on Lunar Energy of July 1989, and might adversely affect the economic feasibility altogether.

Fortunately, some commentators will say, the legal régime under the 1979 Moon Treaty does not provide, by contrast to the sea-bed régime, for such a strict and elaborated system of utilization and its administration, thus, leaving a wider margin of activities for States.

While some experts have speculated whether the "appropriate procedures" under Article 11 para. 5 of the Moon Treaty might lead to the formation of a supranational governmental body, such as the Sea-Bed Authority, it is clear that the States Parties to the Treaty themselves will decide whether or not to create a new Moon Authority, which will be endowed with the functions of an inter-governmental organization.

Reviewing the ensemble of its rules, the Moon Treaty appears to refer to the common heritage of mankind concept as a mere label for the bundle of provisions in the Treaty, establishing a new type of territorial status which consists of the following components:

(1) International law applies to all activities on the Moon (Articles 2 and 4); this rather general clause, it is arguable, promotes a dynamic change of the legal régime, as far as international law is subject to a change on Earth, it might be considered as amended on the Moon.

(2) Article 3 repeats Article IV of the 1967 Treaty providing that the "Moon shall be used by all States Parties exclusively for peaceful purposes", thus, giving rise for the issue, whether "peaceful" amounts to a total non-militarization or merely means, instead, "non-aggressive".

(3) Non-appropriation
Article 11 para. 2 of the Moon Treaty prohibits the national appropriation of any portion of the Moon, which in itself, it appears, does not exclude the appropriation of the resources of the Moon. However, Article 11 para. 3 of the Treaty stipulates:

> "Neither the surface, nor the sub-surface of the Moon, nor any part thereof or natural resources in place, shall become property of any State, international governmental or non-governmental organization, national organization or non-governmental entity or of any

natural person. The placement of personnel, space vehicles, equipment, facilities, stations and installations on or below the surface of the Moon, including structures connected with its surface or sub-surface, shall not create a right of ownership over the surface or sub-surface of the Moon or any area thereof. The foregoing provisions are without prejudice to the international régime referred to in para. 5 of this Article".

It has to be pointed out that the prohibition of appropriation of natural resources applies only to those "in place".

(4) Freedom of scientific investigation Article 6 para. 2 of the Moon Treaty provides for the following rights of States Parties concerning scientific investigations:

(a)"The right to collect on and remove from the Moon samples of its minerals and other substances" which "may be used by them for scientific purposes". It should be noted in this context that the wording carefully avoids the notion property regarding these scientific samples and that the Treaty suggests to all States Parties the desirability of making a portion of samples available to others for scientific purposes.

(b) States Parties may also "use mineral and other substances of the Moon in quantities appropriate for the support of their missions".

(5) Article 11 Para 4. of the Moon Treaty confirms the principle of freedom of exploration and use without discrimination.

(6) Article 9 of the Moon Treaty provides for the freedom to establish manned and unmanned stations subject to the following conditions:

(a) Only the area required for the station may be used;

(b) immediate notification of the location and purpose to the United Nations Secretary-General;

(c) annual report to the United Nations Secretary-General;

(d) free access to all areas of the Moon for other States Parties is not obstructed.

(7) Jurisdiction and ownership over equipment, facilities, space vehicles and personnel remain under the laws of the respective States Parties.

(8) Article 5 para. 1 obliges States Parties to provide the United Nations Secretary-General, the international scientific community and the public with information on their activities on the Moon.

(9) According to Article 7 of the Treaty States Parties have to take appropriate measures to protect and to preserve the environment in their exploration and use of the Moon, and to inform the United Nations Secretary-General of measures being adopted. In particular, States Parties are requested to report to him areas of the Moon regarding special scientific interests.

(10)Article 11 para. 6 establishes the obligation of States Parties to inform the United Nations Secretary-General, the public and the International Scientific Community, to the greatest extent feasible and practicable, of any natural resources they may discover on the Moon with a view to promote the creation of the international régime for the management of the natural resources.

(11)Article 14 para. 1 of the Moon Treaty subjects States Parties to a liability for national activities on the Moon.

IV.
Outlook

In the light of the scope and extent of projects considered by this Conference, it becomes obvious that the mere normative framework of the Moon Treaty described before, not longer suffices, and an institutional structure is required urgently in order to cope with the administration and control of large scale activities such as envisaged under the concepts of SPS and LPS. The present material rules of the Moon Treaty have been appropriate during the exploration phase of lunar activities. Therefore, the time becomes ripe for the establishment of the "international régime, including appropriate procedures, to govern the exploitation of the natural resources of the Moon". According to Article 18 of the Moon Treaty, the creation of the international régime will be considered at any conference convened to review the Treaty. Such a conference will automatically be included in the agenda of the United Nations General Assembly ten years after the entry into force of the Treaty, thus, in 1994, but the conference can also be convened at any time, if requested by one third of the States Parties.

In the absence of a political consent to create the international régime regarding the exploitation of the Moon's natural resources, the dispute arises, whether this means a moratorium on exploitation. Whereas many developing States, advocating a maximum of common heritage of mankind, would suggest such a moratorium, the Moon Treaty itself and its travaux préparatoires do not give evidence in law for the existence of a moratorium. Furthermore, in the light of a preceding controversy on the United Nations General Assembly resolution 2574 D of December 15, 1969, recommending a moratorium on the exploitation of the resources of the sea-bed and ocean floor, the United States delegates, during the drafting of the Moon Treaty, twice alleged that there was no moratorium regarding the Moon without any other delegation challenging this assertion.

However, even in the legal absence of a moratorium, it would be politically wise to consider and to perform any Moon activities on a larger scale with a trustee's conscience. Such a trusteeship minded attitude taken together with a self restraint on unilateral actions might come close to what is meant by "common heritage of mankind".

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SPS 91

C1.16 Topaz optimal source of Electrical Energy for advanced civil space applications

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ABSTRACT

This paper discusses the possible advanced civil space missions for nuclear power systems of the "Topaz" family. Two successful flight tests on-board spacecrafts "Cosmos-1818" and "Cosmos-1867" provided operationability of the system in actual space conditions and made the USSR prestige in thermionic systems development recognized. The design of the "Topaz" system provides nuclear and radiation safety in accordance with the United Nations Organisation recommendations.

RESUME

Cette communication présente les missions spatiales civiles futures qu'on peut envisager pour les systèmes de puissance nucléaire de la famille "Topaz". Deux vols expérimentaux réalisés avec succès à bord des vaisseaux spatiaux "Cosmos 1818" et "Cosmos 1867" ont démontré le bon fonctionnement du système dans des conditions spatiales réelles et ont fait que le prestige de l'URSS dans le développement des systèmes thermoioniques était reconnu. Le concept du système "Topaz" assure la sûreté nucléaire et la protection contre les radiations conformément aux recommandations de l'Organisation des Nations Unies.

Large-scale publications and comments in press conserning the on-ground prototype of space nuclear power system "Topaz-2" make us emphasize the space nuclear power system "Topaz",which was sucsessfully test-flown in 1987-1988 on-board spacecrafts "Cosmos"-series: 1818 and 1867. At the same time we shall review the possible tasks for such space nuclear power systems.

The energy capacity and compactness of these systems are of significant advantage than those of popular now solar converters. The space nuclear power systems (SNPS) do not need sun-wise orientation, do not have large panels with solar elements, do not need the energy storage systems (such as chemical batteries) and is free from the influence of irradiation in space. With the electrical power requirements growth the most valuable become small (in comparison with solar elements) weight-dimentional characteristics and low cost. For comparison:

$$N = 10\ kW_e: \quad \frac{M_{solar}}{M_{SNPS}} \pm 10\%$$

$$N = 25\ kW_e: \quad \frac{M_{solar}}{M_{SNPS}} \sim 2$$

$$N = 50\ kW_e: \quad \frac{M_{solar}}{M_{SNPS}} \sim 4$$

$$N = 100\ kW_e: \quad \frac{M_{solar}}{M_{SNPS}} \sim 6$$

For instance, by the ERATO estimates: for $N = 20\ kW_e$ the cost of SNPS amounts to only 20% from the photovoltaic system of the same electrical power output.

Up to nowadays the SNPS potential was unclaimed, because for two past decades the need in energy for space was limited to several kilowatts.

At present the rapid technology development set a number of large-scale civil informational and communicational missions for Earth population sake, which can be realized by means of space vehicles in late 90-s. Such missions are the following:

- high-definition TV with computer control and individual antennas receiving the world-wide cable TV;

- exchange of information (retransmission communication facilities, computer exchange programs, telegraph-telefaximile facilities);

- direct broadcast by means of large paraboloic-reflector aerials;

- overall trafic control radar systems (airplanes, ships, automobiles and single persons);

- provision of radiolocation maps of Earth surface for navigation and orientation on the demand;

- space-based technology production;

- scientific research, ets.

The realization of these missions will let us be in time with the fast Earth population growth and integration of different regions in all aspects of manufacturing activities, cultural exchange and entertainement. These civil missions goals make it sure to get government support in the course of its realization.

At present energy supply of such missions is realized by means of solar power systems of 3 - 5 kW_e. To realize the above mentioned missions, having in mind operational integration, there will be nesessary a source of energy from 12 to 15 kW_e. In this energy range the advantage in front of solar and compatitive in comparison with other thermoelectric and turbomachine (Briton or Renkine cycles) energy conversion cycles, is after thermionic nuclear power systems. They have a number of unique features that make them particularly attractive for energy production in future advanced space applications:

- the highest heat rejection temperature which ensures small dimentions of radiator and overall power system in comparison to other energy conversion schemes;

- the possibility of obtaining maximum electrical power at set overall dimentions, insignificant dependence of weight versus power growth;

- compactness of the system, no torque moments, providing stable orbital position;

- configurational compatibility of these systems with boosters, the possibility of using electric propultion for satellites orbit transfer and for putting the satellite into the orbit.

Space-based systems are under development in USA, Europe and Japan to realize these missions. In these countries with perspective space programs there is great interest in using the powerfull, compact, long operational lifetime nuclear power systems. High-power energetics is necessary for exploration of near and deep space.

In the USSR the development of nonmachine energy conversion systems was preferred.

In the Soviet Union there were carried out by a number of organizations a wide-scale investigations and developments on thermionic nuclear power systems. The results were published in the Soviet press, from 1971 they were repeatedly announeced at international conferences. The most complete results of these developments were announeced at Symposia on Space Nuclear Power Systems which took place in Albuquerke, USA, 1989-1990, in Obninsk, USSR (1990), at Lion's 1990 Nuclear Forum Exhibition, France, 1990 and in Moscow, 1991 Eurospace Conference.

The efforts on development of thermionic systems test samples, carried out by NPO "Krasnaya Zvezda" in cooperation with other organizations completed with sucsessful flight test of "Topaz" system confirmed the possibility for operation of all the systems components in real space conditions, including the launch and putting into the orbit and under gravity forces. The values of the systems power output parameters obtained at on-ground tests, were proved, as well as control algorithms on the starting and on the nominal regimes of nuclear power systems. These efforts proved the recognized prestige of the USSR and NPO "Krasnaya Zvezda" in thermionic systems development.

One more aspect of using nuclear energy in space is placing on high multiple orbits the high-power energy sources for energy feeding of small established satellites.

Space thermionic power systems have a wide range of possibilities for increasing power level, efficiency and lifetime. Mass characteristics of thermionic systems become better analogous characteristics of solar systems, beginning from average daily electrical power level from about ten kilowatts with specific photovoltaic converters electrical power of up to 180 W/m^2, specific accumulator batteries capacity of up to 35 A/hour and specific impulse of vernier engine for orbit transfer - 2500 sec.

For thermionic nuclear power systems (NPS) producing 20 and more kilowatts of electricity at operational life-time of 5 and more years there may be used heat and fast reactors-generators with in-core multichannel fuel elements having in mind that heat reactor NPS are reasonable at electrical power output of 100 kW_e and fast reactor NPS are reasonable from 100 kW_e to megawatt level.

The design and technology of heat reactor NPS is a further development of designes and technologies of Space Nuclear Power System "Topaz". The heat reactor-generator NPS of this tipe with core dimentions near to minimum possible at mean specific capacities of 2-3 W/sm^2 will provide electrical power of 25-40 kW_e at voltage of 120 V. The NPS mass in this case totals to 2500-2800 kg, dimentions on starting position are: length of about 7 m at maximum diameter 2 m.

The up-graded safety and effectiveness of conversion in comparison with SNPS "Topaz" is provided by using in thermal fuel elements and reactor constructions new constructional materials having a complex of essentially better properties by realizing principally new designers and technology decisions, elements reserving, ensuring enough neutron-physical, mechanical and heat engineering parameters reserves. In NPS there is used special safety system, when the reactor remains undercritical at any accidents when being manufactured, stored, transported and at launch by the spacecraft to the orbit.

NPS "Topaz" was designed for certain technical conditions and certain object. All the designing of NPS was carried out in the NPO "Krasnaya Zvezda", as well as the manufacturing of models and samples of NPS "Topaz" for technological, energy and flight tests. The main features of SNPS "Topaz" are the following:

Electrical output		6 kW
Voltage, const.		32 V
Core dimentions:	diameter	280 mm
	height	364 mm
	outer diameter	460 mm
U^{235} loading		12 kg
T_{max} of heat carrier		610° C
Surface area of cooler-irradiator		7 m^2
SNPS mass (without the start-up accumulator batteries)		1200 kg
SNPS dimentions:	diameter	1,3 m
	length	4,7 m

The important condition for space application of nuclear energy is the guarantee of nuclear radiation safety on all stages of nuclear energy systems exploitation. The nuclear and radiation safety guarantee for orbital tests of SNPS "Topaz" fully coincide with the requirements existing, in particular, developed and accepted by the UN Committee on Peceful Uses of Outer Space, as well as the principles and criteria on safe application of nuclear power systems in space.

The SNPS reactors were started-up to the nominal power by means of automatic control system only after the spacecrafts Cosmos-1818 and Cosmos-1867 were put on the supporting orbits and became the Earth satellites.

In nuclear power systems "Topaz" nuclear safety is ensured by reactor and control systems design, radiational safety, first-of-all, by placing the space objects having nuclear systems in orbits, where the spacecraft ballistic existance time is essentially longer than the time, necessary for total decay of accumulated radioactivity. Thus, exploiting at flight tests of "Topaz" system a high operational orbit (800 km) guarantees the spacecraft existance life-time there for not less than 350 years. This time is enough for complete radioactive fission products decay to safe level. The conditions of total radioactive decay are even more satisfied, in case the spacecraft with nuclear power system is placed on geostationary orbit.

For low-orbit spacecrafts with nuclear power systems it is necessary to provide a disposal system, providing disposal of nuclear reactor to the radiation safe orbit (after seasing lifetime and in case of any accidents onboard the spacecraft) and additional radiation safety systems. For the "Topaz" system it includes the dispersion system in case of emergency leaving the orbit. The most suitable for its mass-dimentional particle dispersion parameters are developed in NPO "Krasnaya Zvezda"- the aerodynamic dispersial system and explosion dispersial system.

A very important curcumstance is that NPS may be boosted for a short period of time to electrical power level of 70-80 kW_e. Such boosting realized in the beginning of campagn, hardly influence the weight-dimentional parameters of NPS. This circumstance may be of effective use for interorbital flights of spacecrafts with electric propultion engines of high specific thrust, which essentially broadens the possibility of payload delivery to high orbits, including geostationary, for putting the spacecraft to the supporting orbit by means of relatively cheap booster, for instance, "Proton". In its turn it opens wide perspectives for using the NPS for informational systems (global telephone communications), universal technological platforms, different kinds of monitoring.

Multi-purpose space platform main data:

Electrical power output is 25-30 kW_e for lifetime 5-7 years.

In the propultion mode of operation (support-to-high orbit transfer, maneuring, correction, stabilization), the Incore Thermionic Reactor can be forsed for up to 2-3 times for a period (in total) of up to one year.

The platform can be provided for launch to geostationary orbit with 6000 kg payload mass and maneuvering on operating orbit, when stationary xenon plasma thrusters with specific impulse of about 30000 m/s and thrust efficiency 70% are used, by spacecraft with 13500 kg mass when on the supporting orbit.

Multi-purpose space platform mass (without propellant) is no more than 4700 kg, including nuclear power plant mass 3100 kg.

U^{235} loading in Incore Thermionic Reactor core is 41 kg.

We can definately say, that our country is essentially ahead of Worlds' developments in the field of designing and employing of such perfect space nuclear power systems, as thermionic SNPS. Our "Topaz" system is nowadays beyond compare. SNPS of "Topaz" family are some of the perspective electrical power sources for spacecrafts of long-term power levels from 50 to 100 kW_e and lifetime of up to 5-7 years, which coinsides with the optimal periods of modernization of technology for objects of application. Such systems offer great potential for space developments. They have exellent electric characteristics, they are compact, have stable and relible performance and they offer essential increace of payload mass (or use smaller boosters) BECAUSE OF JET enjines. In Space Nuclear Power Systems there is used a special safety system, which maintains the reactor undercritical at any possible accidents, including the manufacturing, storing, transporting and putting into the orbit by a spacecraft.

The most perspective are the designes for energy supply of satellites, for orbital spacecrafts, for manned Mars missions, when thre is need in essential sources of electrical supply and power supply for the engines. A very perspective one is the project of Lunar electrical power station.

C1.17 Extraterrestrial resources: A metallogenical typology

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ABSTRACT

NUMEROUS EXTRATERRESTRIAL RESOURCES EXPLOITATION PROGRAMS HAVE BEEN SUGGESTED SINCE THE END OF THE EIGHTIES. A WELL DEFINED CLASSIFICATION OF THE OBJECTIVES WILL BE REQUIRED IF THIS EXPLOITATION IS TO BE RATIONALLY ORGANISED. A METALLOGENICAL STUDY COULD LEAD TO A TYPOLOGY OF THESE RESOURCES, ALLOWING THE OBJECTIVES OF A LONG TERM EXPLOITATION TO BE HIERARCHICALLY SORTED.

ABSTRACT

DES PROPOSITIONS D'EXPLOITATION DE RESSOURCES EXTRA-TERRESTRES TRÈS DIVERSIFIÉES ONT ÉTÉ SUGGÉRÉES DEPUIS LA FIN DES ANNÉES 80. UNE CLASSIFICATION RIGOUREUSE DE CES OBJECTIFS SERA NÉCESSAIRE SI L'ON VEUT ORGANISER RATIONNELLEMENT CETTE EXPLOITATION. UNE ÉTUDE MÉTALLOGÉNIQUE DE CES RESSOURCES PEUT DÉBOUCHER SUR UNE TYPLOGIE PERMETTANT DE HIERARCHISER LES OBJECTIFS D'UNE EXPLOITATION À LONG TERME.

INTRODUCTION

La conquête de nouveaux territoires a toujours eu pour corollaire la recherche de nouvelles richesses. Si l'on en juge par les projets développés depuis plus de 30 ans, la conquête spatiale ne semble par devoir déroger à cette règle.

Encore peu abordée, l'idée d'exploiter des ressources extra-terrestres a été relancée à l'occasion du discours prononcé le 20 juillet 1989 par George Bush.

La perspective d'une exploration humaine des planètes a donné lieu à nombreuses propositions où revenait souvent l'argument d'exploitation comme un moyen de viabiliser, de rentabiliser, et de justifier une telle mission. Il apparaît aujourd'hui important de replacer ces suggestions dans un même cadre typologique à fin de comparaison et d'évaluation. L'objectif de cet article est de montrer qu'une classification de type métallogénique se prête particulièrement à cet exercice, compte tenu de l'expérience acquise sur Terre dans ce domaine.

I - L'INTERET D'UNE CLASSIFICATION METALLOGENIQUE POUR L'EXPLOITATION FUTURE DES RESSOURCES EXTRA-TERRESTRES

La métallogénie est une science appliquée qui étudie les gisements de matières premières minérales et énergétiques afin d'appréhender les mécanismes de leur mise en place et d'élaborer des hypothèses sur leur mode de gisement et leur localisation.

L'étude métallogénique d'une ressource utile consiste en une chaîne analytique débouchant sur la notion d'exploitation : en amont de la chaîne, exploration, prospection, étude de rentabilité, et méthodes de traitement débouchent en aval sur la notion de faisabilité. Ce même type de raisonnement, couramment appliqué sur Terre, peut s'étendre aux ressources extra-terrestres.

Il importe, comme préalable à l'exploitation, de connaître cubage, composition, et localisation exacte des ressources, afin de disposer de données suffisantes pour mettre en place une exploitation lorsque les perspectives économiques et les capacités techniques auront atteint leurs seuils de rentabilité et de faisabilité.

Par exemple, cette approche peut tout aussi bien s'appliquer à l'exploitation d'oxygène lunaire qu'aux schistes bitumineux ou encore aux champs de nodules polymétalliques des plaines abyssales.

L'argument principal justifiant l'étude d'exploitations in situ de ressources extra-terrestres est un argument économique : le coût des missions est grevé par la masse à arracher à l'attraction terrestre. Disposer de carburant ou de matériaux de construction à partir de la Lune, de Mars ou des Astéroïdes serait un facteur important de réduction de cette masse, et donc de coût. Cela permettrait d'envisager des missions lointaines, et de s'affranchir partiellement du segment Terre-orbite basse. Toutefois, si économie il y a, elle ne peut se concevoir que comme une économie d'échelle, compte tenu des investissements énormes en

recherche et en expérimentation, ainsi que de la mise en place, et de la maintenance d'usines de traitement et de mines "pilotes" extra-terrestres.

Le terme "exploitation des ressources extra-terrestres" regroupe tout un ensemble de projets, dont certains sont réalisables à plus ou moins long terme, tandis que d'autres demeurent très prospectifs. Il appartient avant tout de **classer** ces ressources en fonction de leur origine, de leur nature, de leurs applications et du degré de certitude scientifique quant à leur existence, qui dépend essentiellement de la connaissance du contexte planétologique.

II - UN EXEMPLE DE CLASSIFICATION TYPOLOGIQUE

Une classification possible des ressources extra-terrestres est proposée sur le tableau ci-contre (fig. 1), en fonction de leur origine.

On voit qu'une partie des ressources citées ne sont pas à proprement parler des ressources d'origine extra-terrestres, mais des objets manufacturés gravitant autour de la Terre, et dont l'utilisation peut être programmée à l'avance. On peut citer par exemple l'utilisation des réservoirs externes de la Navette comme modules d'habitation pour une

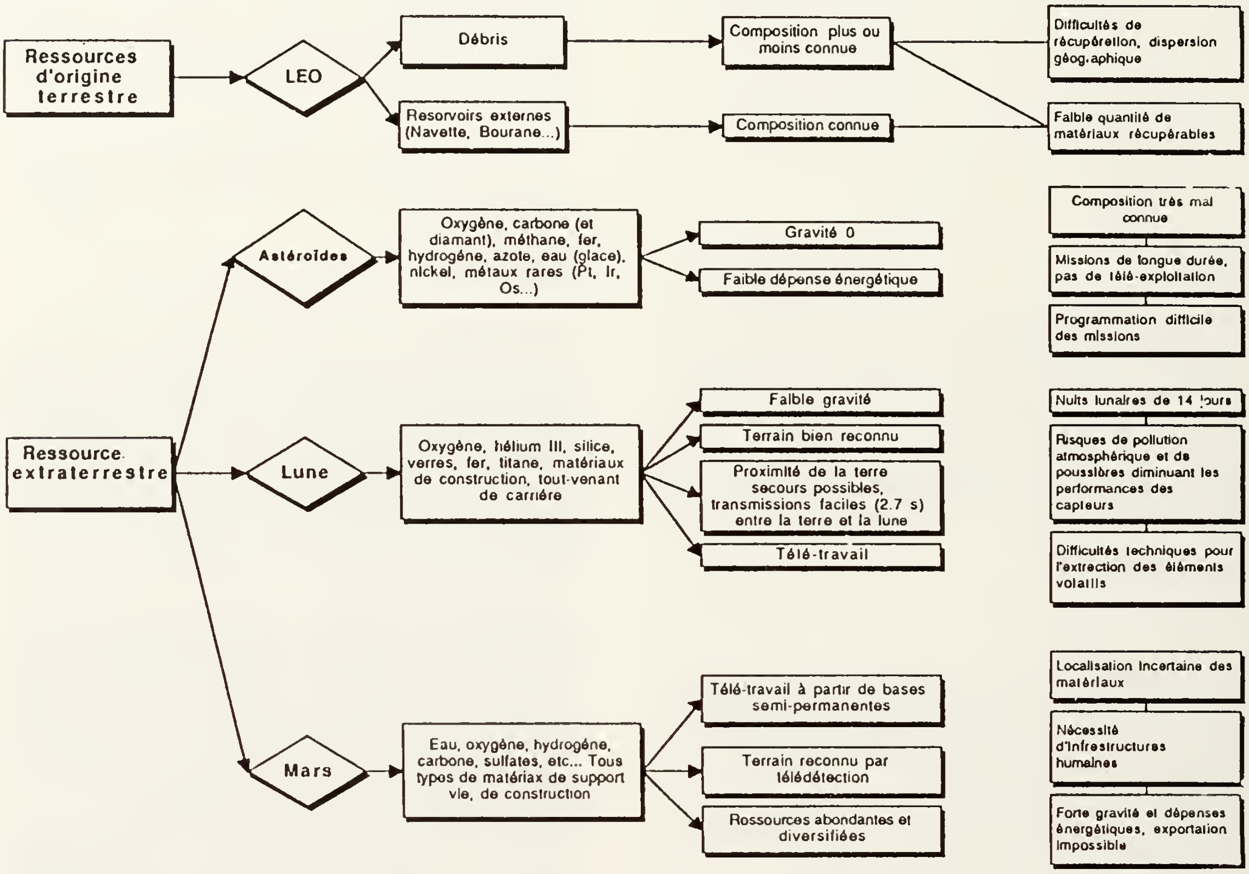

FIGURE 1 : CLASSIFICATION TYPOLOGIQUE DES RESSOURCES EXTRA-TERRESTRES EN FONCTION DE LEUR LOCALISATION

base lunaire[1], ou encore pour la production de poudre d'aluminium[2]. Nous ne reviendrons pas sur ce type d'exploitation.

1 - Les matériaux de construction

Ce tableau fait apparaître que certaines des ressources exploitables répondent à un besoin immédiat, et sont directement utilisables avec ou sans intervention de mise en forme : régolite lunaire, ou martien , exploité en carrière et en tout-venant.

Les propriétés physiques du régolite en font un matériau isolant, réfractaire, peu cohérent, à granulométrie calibrée. Si ces propriétés en font un matériau de choix pour l'isolation thermique et pour protéger des radiations, par exemple pour une base habitée lunaire[3], elles en font aussi un matériau difficile à façonner par pyrolyse, à moins de disposer de températures très élevées. Par ce biais, on obtiendrait des briques ou des moëllons à texture vitreuse. Ce même type de traitement s'appliquerait aux scories de fusion et au laitier silicaté, sous-produits de pyrolyse de roches lunaires.

2- Support-vie

Une deuxième catégorie regroupe l'ensemble des matières pouvant intervenir dans l'élaboration de support-vie (O2, H2O), et dont l'exploitation à petite échelle servirait d'appoint à des bases habitées lunaires ou martiennes. On peut citer la bio-exploitation du CO2 martien par des installations algales photo-synthétiques, ou encore l'extraction d'oxygène par des processus pyro-métallurgiques coûteux en énergie. Une autre solution consiste en l'extraction de C, H, H2O à partir des chondrites carbon ées de la ceinture d'astéroïdes[4].

3 - Exploitations des matières premières énergétiques

Un troisième type d'exploitation concerne les ressources énergétiques : énergie solaire, énergie éolienne sur Mars, et oxygène extrait depuis les roches lunaires ou martiennes et stocké sous forme d'ergols. Les procédés d'extraction se rapprocheraient de ceux mis en oeuvre pour l'extraction de support-vie.
L'oxygène entre dans la structure de la plupart des roches lunaires. L'extraction de cet oxygène par pyrolyse, bien qu'offrant un faible rendement et consommant beaucoup d'énergie est dans le domaine du possible. Les solutions envisagées sont nombreuses. A.H. Cutler (1985) décrit l'extraction d'O2 par réduction de l'ilménite (FeTiO3), minéral fréquent dans les roches lunaires, alors que D.L. Anthony et Al.[5] proposent une extraction par réduction et électrolyse de l'anorthite (Fig. 2a). Ce type de réaction nécessite 5 à 7 Mw pour une production de mille tonnes de O2. Enfin, R.D. Waldron (1989)[6] décrit une chaîne opératoire aboutissant à l'extraction d'oxygène à partir des spinelles, par oxydation partielle du magma et électrolyse en solution acqueuse acide à basse température (Fig.2b).

L'extraction d'oxygène à partir de roches lunaires ou martiennes vise avant tout à produire des ergols. Un autre type de ressource énergétique est l'isotope 3 de l'hélium véhiculé par le vent solaire, et piégé par le régolite lunaire, au même titre que d'autres substances volatiles, l'azote et l'hydrogène. L'exploitation de l'He 3 à partir du régolite est un argument souvent avancé pour une exploitation rentable de la Lune. En effet, l'He 3, sous forme liquide, pourrait devenir, dans la mesure où les processus de fusion seraient maîtrisés, l'une des sources d'énergie du futur. Or, l'exploitation de l'He 3 apparaît relever à l'heure actuelle plus de l'hypothèse que de la réalité scientifique. En effet, on ne dispose que de très peu de données sur les teneurs de ce gaz dans le régolite, et surtout on ignore sous quelle forme exacte il est piégé. Si le flux de particules véhiculées par le vent solaire est de l'ordre de 50g/s, les gaz piégés représenteraient 10^{-5} de la masse du régolite, et des teneurs de l'ordre du ppm. Il faudrait, en extrapolant les données analytiques obtenues sur 7 kg de régolite échantillonné, exploiter et décaper des millions de tonnes de régolite pour en extraire quelques tonnes d'He 3 !

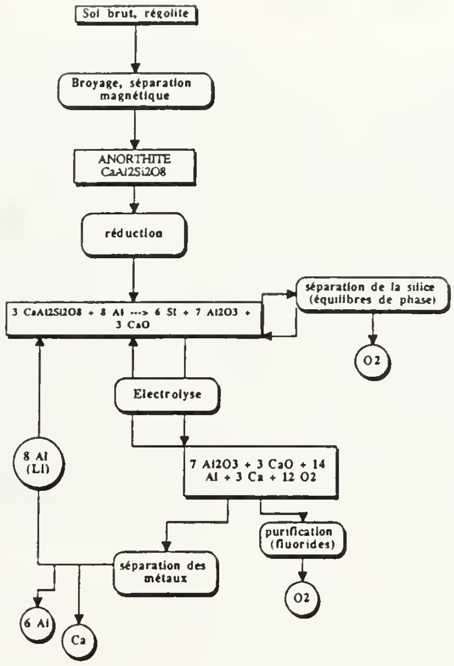

FIGURE 2A : TRAITEMENT DE L'ANORTHITE

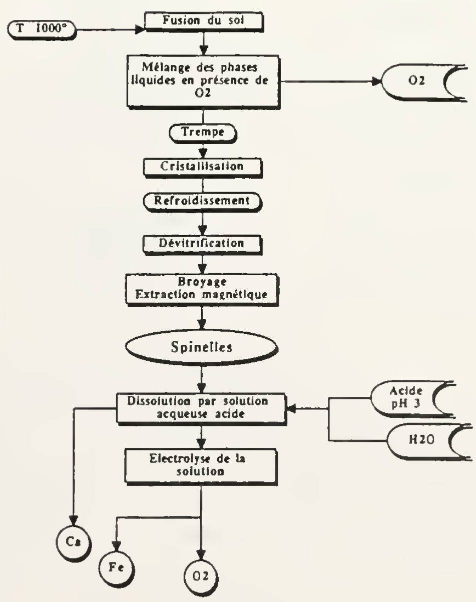

FIGURE 2B : EXTRACTION D'O2 PAR OXYDATION PARTIELLE DU MAGMA

4 - Métaux et métaux précieux

Enfin, dernière catégorie de ressources exploitables, les métaux, soit en sous-produit de pyrolyse (Fe, Ti, Al), soit par extraction directe, comme par exemple Ni et Co à partir de roches ultrabasiques.
Certains corps de la ceinture d'astéroïdes sont constitués de Fe et Ni. Mais le principal intérêt des astéroïdes réside surtout en leur relative richesses en éléments sidérophiles, et notamment en iridium (500 ppm contre un clarke de 1 ppb sur Terre) et en platinoïdes. Les méthodes d'extraction font appel à des techniques utilisées sur Terre, par flux gazeux de Co à température modérée. Sous ces conditions, les composés de Fe et Ni réagiraient en formant des composés carbonyl, selon une réaction de type Ni + 4 Co ---------> Ni (Co) 4. Ce type de gaz peut, par condensation sélective, déposer son contenu métallique, Co, Ir, ou platinoïdes (rhénium, osmium, ruthénium), avec en sous-produit or et argent.

III - Métallogénie extra-terrestre : technique et prospection

Ce paysage des ressources exploitables masque les difficultés inhérentes à leur exploitation proprement dite. Nous ne ferons que citer les difficultés légales liées à l'exploitation et à l'appropriation de ressources spatiales à des fins lucratives, et pour lesquelles il faudrai bâtir des textes de loi régissant leur concession. Nous ne détaillerons que les difficultés relatives à l'exploitation proprement dite et au traitement du minerai.

1 - Prospection

Exploiter une ressource suppose d'en connaître avec précision sa localisation, la nature minéralogique de son encaissant et sa teneur exacte. Ceci suppose, en amont, une phase de prospection et de reconnaissance, s'appuyant sur la télédétection à grande résolution spatiale et spectrale, et sur un échantillonnage représentatif. La maille de l'échantillonnage dépend essentiellement de la teneur et des lois de répartition de l'élément ; ainsi, les teneurs en He 3 calculées sur quelques échantillons ne sont pas représentatives des teneurs globales de cet isotope sur la Lune. Il faudrait resserrer la maille des prélèvements pour obtenir une cartographie détaillée de la répartition de l'élément, et optimiser les sites d'exploitation retenus. Ce type d'étude, bien que coûteux au départ permet de substantielles économies pour une exploitation à long terme, dont elle assure une planification rigoureuse.

La phase de prospection doit s'appuyer sur une bonne connaissance des processus de concentration aboutissant à la genèse d'un gisement, c'est à dire à une anomalie circonscrite dans l'espace. Sur terre, les principaux facteurs de concentration sont la tectonique, l'eau et l'existence de métallotectes, ou de structures vecteurs d'anomalies géochimiques. Si la Lune apparaît comme un corps peu différencié, il en va différemment pour les " planètes terrestres ". Mars par exemple montre des traces d'écoulement d'eau, et des vestiges d'étendues liquides, disparues par évaporation. Il est fort probable que l'eau ait agi en tant que facteur d'érosion et d'altération, remobilisant les substances utiles, redéposées ailleurs dans des pièges structuraux ou sédimentaires. On peut s'attendre ainsi à trouver des halogénures ou des sulfates à la surface de Mars. Vénus et Mars montrent une forte activité volcanique, ainsi que des phénomènes tectoniques intenses. Il est donc probable que des processus de concentration se soient produits. Il faudra donc resserer la maille des observations, afin de mieux appréhender la cartographie minéralogique.

2 - Extraction

Les méthodes évoquées sont essentiellement l'exploitation " à ciel ouvert ", en carrière. Ce type d'exploitation récupère le tout-venant, donc s'applique à des exploitations de matériel à teneur constante, et suppose un tri sévère, aboutissant à du minerai concentré. L'inconvénient majeur de ce type d'exploitation est sa faible sélectivité. Le minerai doit être réduit à une fraction granulométrique homogène par concassage, puis trié. Sur Terre on utilise essentiellement la flottation et le tri gravitaire. Il est difficilement concevable d'utiliser l'eau dans l'espace. Les techniques de tri sélectif seront à adapter au cas par cas : séparation magnétique pour l'ilménite, centrifugation, sublimation ...
A tous ces stades, se pose le problème de la pollution, aussi bien celle du vide spatial par les produits d'exploitation, que par les poussières découlant d'une exploitation à ciel ouvert. En faible gravité la sédimentation des poussières est très lente et l'extraction risque d'engendrer des nuages de pollution, s'infiltrant dans les mécanismes et masquant le ra yonnement solaire.

3 - Traitement du minerai

Nous avons vu que le procédé le plus souvent envisagé est la pyrolyse, couplée ou non à la réduction par l'hydrogène ou le carbone. Ces traitements supposent d'importer des quantités non négligeables de produit depuis la Terre, produits à recycler en fin de traitement. Ces produits, par exemple l'hydrogène ou bien des fluorures, s'avèrent pénalisants et créent une situation de dépendance depuis la Terre.

Il est difficile d'estimer le rendement précis des exploitation, quand bien même le processus serait bien modélisé. En effet, sous des conditions de microgravité, on ne sait que peu de choses des courbes de phases des différents constituants à traiter.
Un autre facteur de risque est la grande amplitude thermique, qui affecterait les machines, par des cycles brutaux de dilatation et contraction.

4 - Stockage des produits

En fin de cycle de production, les produits extraits, qu'il s'agisse d'ergols ou par exemple d'He 3 doivent être conditionnés et stockés en vue de leur utilisation ou de l'exportation. Ici encore, l'amplitude

thermique, le vide et la faible gravité soulèvent de nombreux problèmes et imposent la mise en place de sites de stockage homéothermes, avec des systèmes de réfrigération qui supposent d'importer depuis la Terre des fluides frigorigènes adéquats.

CONCLUSION

Le tableau de la figure 3 regroupe les principales ressources utiles en fonction de leurs applications : de ce tableau se dégagent plusieurs objectifs :

Exploiter la Lune

Coloniser Mars

Explorer les Astéroïdes

Ces trois objectifs s'inscrivent dans une même stratégie : l'exploitation économique de l'espace, et passent par l'établissement de bases avancées autonomes permettant de s'affranchir de la contrainte terrestre et de fournir l'énergie et les ressources nécessaire à des voyages interplanétaires. A l'heure actuelle, cette stratégie apparaît incontournable pour la conquête de l'espace.

CETTE STRATÉGIE À LONG TERME NÉCESSITE DE MENER DE FRONT :

Une approche expérimentale : l'exploitation des ressources identifiées à l'heure actuelle suppose la mise au point expérimentale de méthodes d'extraction en microgravité, ne faisant pas appel à l'hydrogène, avec des fondants et des catalyseurs.

Une prospection rigoureuse : un besoin d'exploration afin de comprendre les mécanismes de formation des planètes, pour connaître et appréhender de façon qualitative la localisation des ressources, et d'identifier des processus de concentration. Cette démarche permettra d'extrapoler, et donc de prévoir les gisements potentiels, et permettra ainsi d'économiser de coûteuses missions de reconnaissance.

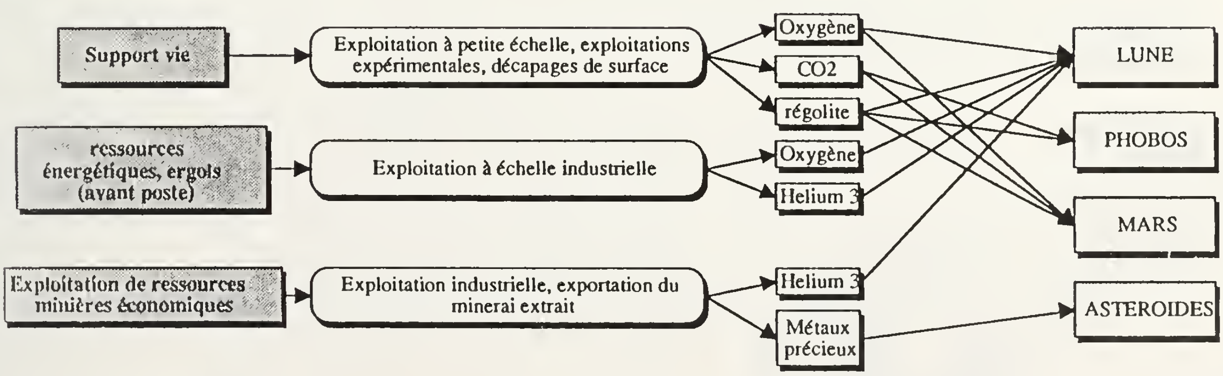

FIG 3 : **RESSOURCES EXPLOITABLES EN FONCTION DES APPLICATIONS**

Enfin, l'exploitation de ressources énergétiques et de matériaux de support-vie permet une autonomie, et donc d'envisager des missions lointaines à l'heure actuelle irréalisables, elle permet de rechercher plus loin de nouvelles ressources. En corollaire, l'exploitation d'objectifs économiques deviendrait réaliste, et on peut envisager, par exemple, l'exploitation de platine depuis les Astéroïdes. Reste à savoir si, à long terme, les désidérata industriels et la priorité accordée aux métaux précieux resteront les mêmes, et si une stratégie d'exploitation économique peut s'accomoder des délais imposés par la conquête spatiale.

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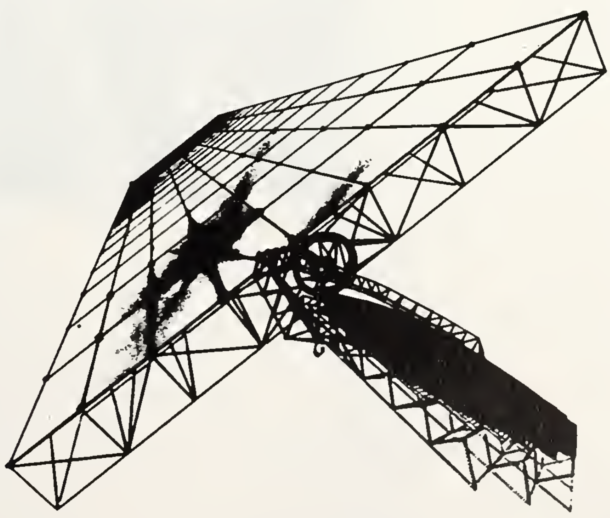
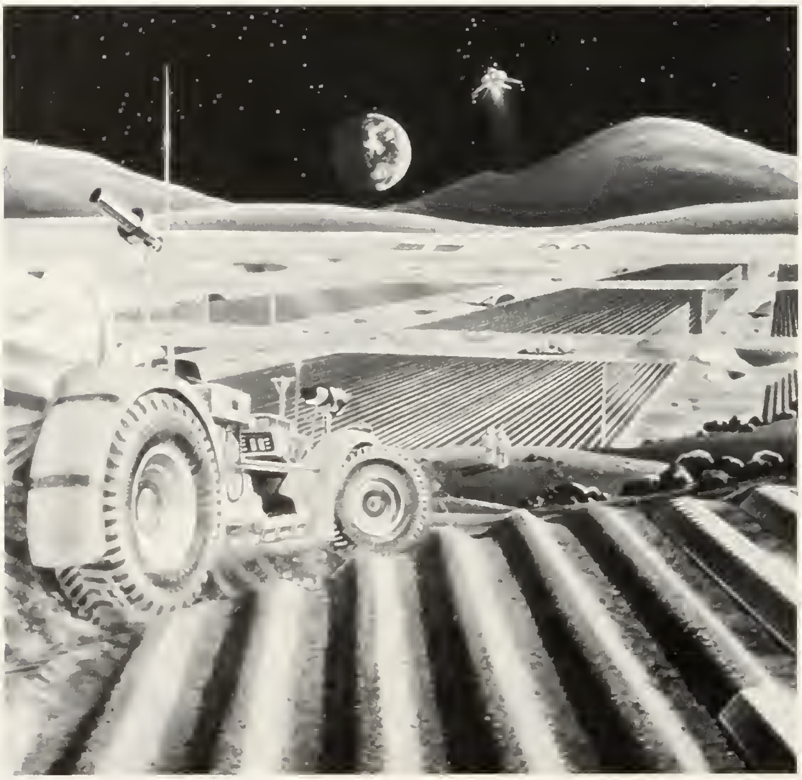


SPS 91

POWER FROM SPACE


Lunar Power System

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A

B

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J

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L

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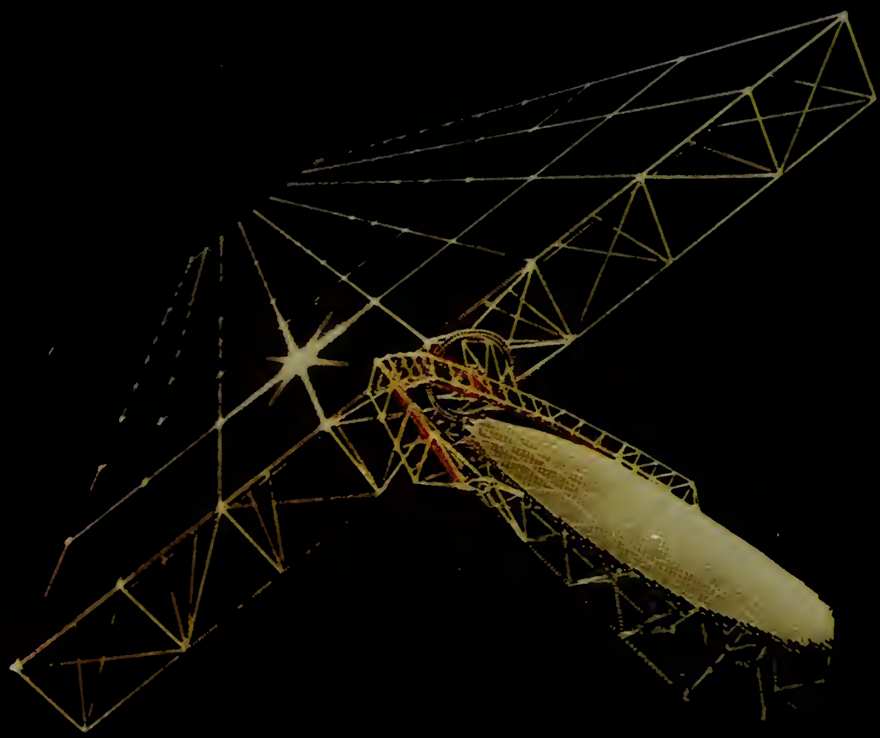
Rectenna

SPS 91



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